Instantaneous three-dimensional flow structure in a suction sump by 3D-PTV and UVP measurements

Katsuya Hirata[1*], Yuki Nakatani[1], Katsuhisa Inagaki[1] and Jiro Funaki[1]
[1] Department of Mechanical Engineering, Doshisha University, Kyoto 610-0321, Japan
(khirata@mail.doshisha.ac.jp).

When we design the suction sumps and the suction pipes, we should know the flow and the air-entrainment mechanism more precisely, to prevent the air entrainment. In the present study, we try to reveal the instantaneous and three-dimensional flow structures in the suction sumps, because the strong unsteadiness and three-dimensionality of such flow. Specifically, we conduct consecutive flow-velocity measurements in a suction sump both by a three-dimensional particle tracking velocimetry (referred to as 3D-PTV) and an ultrasonic velocity profiler (UVP), assisting each other. As a result, we have confirmed a good agreement on time-mean three-dimensional velocity distributions between the 3D-PTV and the UVP. In addition, we reveal some typical flow structures in the sump by the 3D-PTV, which suggest the relationships with the air entrainment.

Keywords: Pump, Water Tank, Two-Phase Flow, Suction Sump, Suction Pipe

1 INTRODUCTION

In power generation plants, irrigations, drainages and so on, the optimum designs of suction sumps have been needed to get low initial/running costs, compact size, high efficiency and high performance. In recent years, we require higher-level solutions for those needs. In such situations, the air entrainment into suction-pipe intakes becomes easy to occur. The air entrainment often induces vibrations, noises, low pumping efficiencies or pumps' collapses at the worst (see ref. [1]). There have existed some systematic studies on the occurrence conditions of the air entrainment (see refs. [2-3]). However, when we design the suction sumps and the suction pipes, we should know the flow and the air-entrainment mechanism more precisely, to prevent the air entrainment.

There have been some investigations concerning the flow observations inside the suction sumps [4-6]. Recently, Funaki et al. [7] reported the quantitative observations using an ultrasonic velocity profiler (referred to as UVP) [8], and they revealed the three-dimensional flow structures. However, their results are time-mean ones due to the characteristics of the UVP.

In the present study, we try to reveal the instantaneous and three-dimensional flow structures in the suction sumps, because of the strong unsteadiness and three-dimensionality of such flow. Specifically, we consider one of the simplest geometries, that is, a straight channel with a rectangular crosses section and a simple and vertical suction pipe near the end of the channel. We conduct consecutive flow-velocity measurements in a suction sump both by a three-dimensional particle tracking velocimetry (referred to as 3D-PTV) [9] and an UVP, assisting each other. While the 3D-PTV technique gives us the information of three-dimensional flow structure, we can measure a velocity profile with high reliability and steadiness by the UVP. In addition, we try to reveal some typical flow structures in the suction sump by the assured 3D-PTV.

2 EXPERIMENTAL METHOD

2.1 Suction Sump and Suction Pipe

Figure 1 shows the present model, which is a simple system of a suction sump and a suction pipe. D and d are the outside and inside diameters of the suction pipe, respectively. A former is used as a characteristic length scale. The latter is fixed to $0.9D$. The suction-pipe intake has a bell-mouth shape. The suction pipe is placed on the center line of the suction sump, taking its axis vertical. B, X and Z denote the breath of the suction sump, the back clearance (namely, the distance from the suction-pipe center to the suction-sump back wall) and the bottom clearance (namely, the distance from the suction-pipe intake to the suction-sump bottom), respectively. H is water level, then, the suction-pipe submergence $S = H - Z$.

A characteristic velocity scale is the mean flow velocity V_i at the suction-pipe intake, which is defined as

$$V_i = 4Q/(\pi D^2). \quad (1)$$

Q is the volumetric flow rate into the suction pipe. Then, we define the Froude number Fr, the Reynolds number Re, the Bond number Bo and the Weber number We as follows.

$$Fr = V_i/(gD)^{0.5}. \quad (2)$$

$$Re = V_i D/v. \quad (3)$$

$$Bo = \rho g D^2/\sigma. \quad (4)$$

$$We = V_i(\rho D/\sigma). \quad (5)$$

Here, g, v, ρ and σ denote the gravitational acceleration, kinetic viscosity, fluid density and water-to-air surface tension, respectively.

Table 1 shows the present experimental parameters. Tested cases are three, that is, cases A, a and b. The case A is for the accuracy check of the 3D-PTV with the UVP. On the other hand, the cases a and b are for the consecutive observations of instantaneous and three-dimensional flow structures, using the assured 3D-PTV. Precisely speaking, we do not observe the air entrainment in the case a, and we often observe it with "spatially-continuous air strings" in the case b.

In the present coordinate system, the origin O is on the suction-pipe center and on the suction-sump bottom. The *x* and *y* axes are horizontal ones. The former and the latter are parallel and perpendicular to the suction-sump channel flow, respectively. And, the *z* axis is vertical one.

Table 1: Experimental parameters.

	Case A	Case a	Case b
D [mm]	38	32	
d [mm]	34	27	
B/D	3.16	3.15	
X/D	1.58	1.71	
Z/D	0.39	0.71	
S/D	1.19	2.0	1.0
Fr	0.98	1.8	
Re	2.2×10^4	3.2×10^4	
Bo	200	140	
We	14	21	

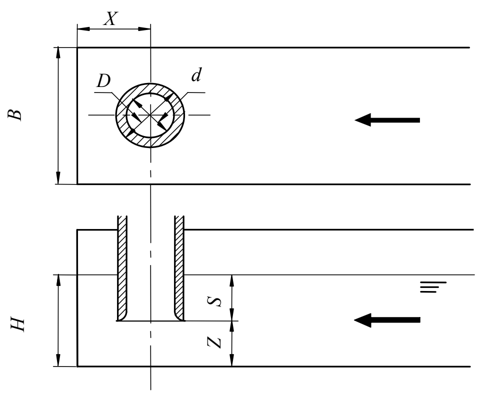

Figure 1: Model; suction pipe and suction sump. *B*, Sump breath; *D*, outside diameter of a suction pipe; *d*, inside diameter of a suction pipe; *H*, water level; *S*, submergence depth; *X*, back clearance; *Z*, bottom clearance.

2.2 Experimental apparatus

The present experimental apparatus is composed of a closed water-circulation system. A turbo pump feeds working fluid (water) to a suction sump from a reservoir tank. We control the flow rate of the pump by a control valve, and then control the water level *H* in the suction sump. At the upstream of the suction sump, namely, at 0.84 [m] upstream from the suction-sump back wall, we put a filter to get a uniform flow. The filter consists of unwoven fabric, sandwiched by two wire meshes with a diameter of 0.001 [m] and a grid size of 0.001 [m]. Another turbo pump feeds water up from the suction sump into a suction pipe. We measure the flow rate *Q* using a flow meter. Water from the flow meter falls into the reservoir tank, then a water-circulation system is closed.

2.3 UVP system

In the present study, we use a UVP monitor of UVP X-2-PS by Met Flow SA with a frequency of 4 [MHz]. The number of measuring points is 128 in one profile, and then, the space resolution on the profile is 0.75 [mm]. As the diameter of the ultrasonic beam is 5 [mm], one measuring volume is a disc with a diameter of 5 [mm] and with a thickness of 0.75 [mm]. We get consecutive 1024 profiles at each measurement with an interval of 32 [ms] or more. When we get time-mean velocities, we average more than 200 profiles, which is previously confirmed to be enough for the present cases. Tracers are bridged polyethylene particles with a mean diameter of 1.2×10^{-5} [m] whose density is controlled to become the same density of water.

2.4 3D-PTV system

Figure 2 shows the experimental apparatus with a 3D-PTV system. As 3D-PTV tracers, we use bridged polyethylene particles with a mean diameter of 1.8×10^{-4}[m], whose density is controlled as well. Tracer particles suspended in water are irradiated by a YAG laser. We take stereo photographs using two high-speed video cameras with a frame rate of 500 [frames/s] fixed outside the back and sidewalls, which are controlled by a PC. For each the 3D-PTV analysis, we use four successive stereo photographs.

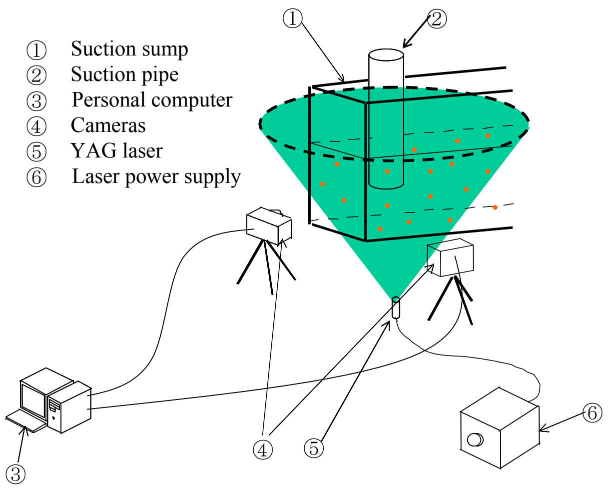

Figure 2: Experimental apparatus with a 3D-PTV system.

3 RESULTS AND DISCUSSION

3.1 Time-Mean Flow Field by 3D-PTV and UVP

In order to confirm the accuracy of the present 3D-PTV measurements, we compare the time-mean velocity distributions in the case A by the 3D-PTV with those by the UVP. Figures 3 and 4 show the velocity vectors on the *x*-*z* planes, and Figures 5 and 6 show the velocity vectors on the *y*-*z* plane. Here, Figures 3 and 5 are obtained by the 3D-PTV, and Figures 4 and 6 by the UVP.

As a result, we have confirmed qualitative agreements between the 3D-PTV and the UVP results. Namely, in both Figures 3 and 4, we see a downwash just in the downstream of the suction pipe, and a recirculating flow between the suction pipe and the suction-sump back wall. In both Figures 5 and 6, we can see a pair of clear and large longitudinal vortical structures, which induce a strong upward flow near the suction-sump center.

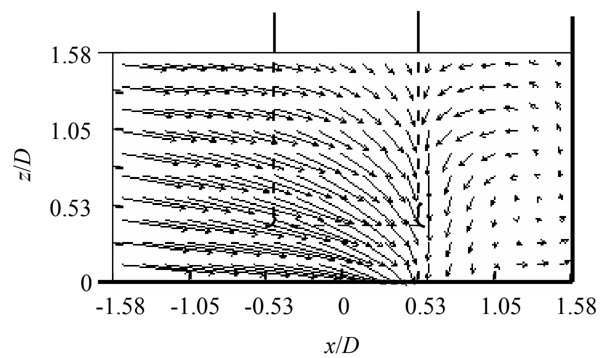

Figure 3: Velocity vectors on the *x*-*z* plane by 3D-PTV (case A, *y*/*D* = -0.94).

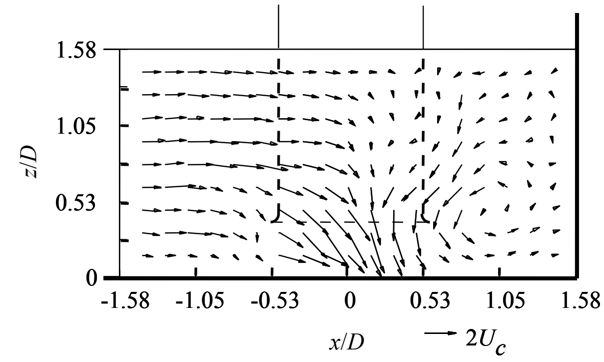

Figure 4: Velocity vectors on the *x*-*z* plane by UVP (case A, *y*/*D* = -0.63).[8]

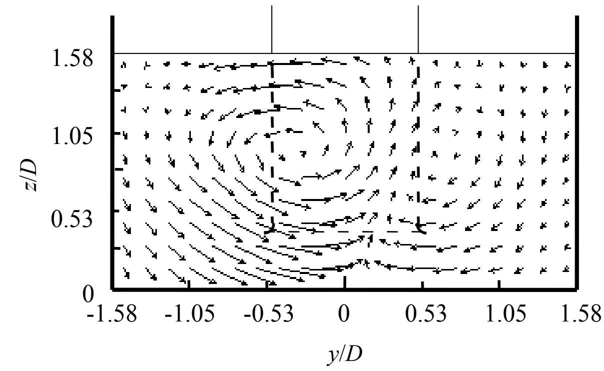

Figure 5: Velocity vectors on the *y*-*z* plane by 3D-PTV (case A, *x*/*D* = 1.24).

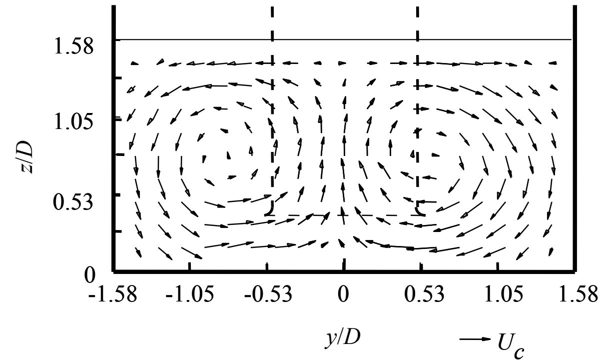

Figure 6: Velocity vectors on the *y*-*z* plane by UVP (case A, *x*/*D* = 0.63).[8]

3.2 Flow Visualization around a Suction Pipe by 3D-PTV

Now, using the 3D-PTV system assured in the above, we show some instantaneous and three-dimensional typical flow structures in the suction sump.

Figure 7 shows a sample result in the case a by the 3D-PTV, that is a set of velocity vectors in the three-dimensional space at an instant. The obtained vectors seem acceptable everywhere in the visualized whole space. However, it is not easy to understand the three-dimensional structure, owing to the intrinsic limitation of two-dimensional plane maps.

By interpolations and the integrations on Figure 7, we get Figure 8, that is, the streamlines which exist near the free surface in the upstream. Such streamlines are appropriate to consider the air entrainment from the free surface. The streamlines pass over the suction pipe toward the back wall descending down, and reach to the suction-sump intake via the vicinity of the bottom wall. Note that, as we can not obtain the velocity vectors just near walls, some of the streamlines terminate near the back wall. The termination tends to appear for the streamlines near the free surface at the upstream.

Figure 9 shows the streamlines which exist near the free surface in the upstream. As well, the streamlines pass over the suction pipe descending down, and finally reach to the suction-pipe intake. However, we can not find such streamlines as terminate near the back wall, because all the streamlines descend down apart from the back wall. It seems consistent that we observe the air entrainment with the flow structure in Figure 9 more commonly, than that in Figure 8.

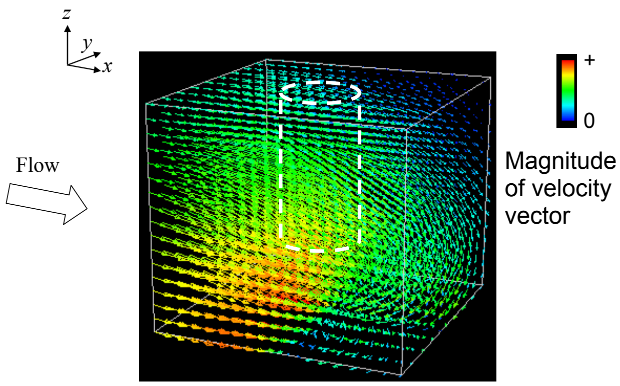

Figure 7: Velocity vectors by 3D-PTV (case a).

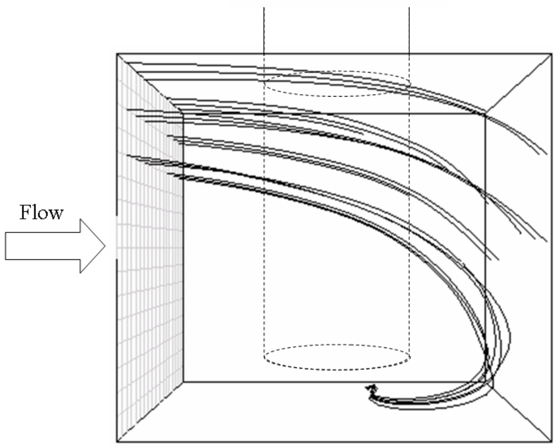

Figure 8: Streamlines by 3D-PTV (case a).

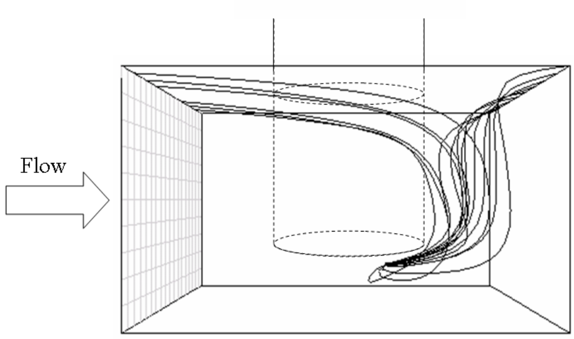

Figure 9: Streamlines by 3D-PTV (case b).

4 CONCLUSIONS

As an accuracy check, we have confirmed a good agreement on time-mean three-dimensional velocity distributions between the 3D-PTV and the UVP. In addition, the authors reveal some typical flow structures in the sump, and discuss the relationship between the flow structures and the air entrainment.

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