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Image Analysis of Fine Structures of Supercavitation in the Symmetric Wake of a Cylinder

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***Abstract*—**The fine structure of supercavitation in the wake of a symmetrical cylinder is studied with high-speed video cameras. The flow is observed in a cavitation tunnel at the speed of 8m/sec when the sidewall and the wake are partially filled with the massive cavitation bubbles. The present experiment observed that a two-dimensional ripple wave with a wave length of 0.3mm is propagated in a downstream direction, and then abruptly increases to a thicker three-dimensional layer. IR-photography recorded that the wakes originated from the horseshoe vortexes alongside the cylinder. The wake was developed to inside the dead water zone, which absorbed the bubbly wake propelled from the separated vortices at the center of the cylinder. A remote sensing classification technique (maximum most likelihood) determined that the surface porosity was 0.2, and the mean speed in the mixed wake was 7m/sec. To confirm the existence of two-dimensional wave motions in the interface, the experiments were conducted at a very low frequency, and showed similar gravity waves in both the upper and lower interfaces.

***Keywords*—** Supercavitation, density gradient correlation

I. Introduction

THE supercavitation of a cylinder can be seen in its wake in a low-pressurized water tunnel. The symmetric shape of the interfacing line between the water and the vapor begins from points nearly at the top and the bottom of the cylinder. The shapes of the wakes are quite different according to the flow speeds and the back pressure in the water tunnel. Due to the fine structure of the phenomena, the seeds of the cavitation bubbles are micron-sized. They then merge and grow to larger bubbles in the flow and, eventually, as a large group of bubbles, they merge again to form a dead water zone. As the flow speed increases, the closed line becomes longer and eventually forms parallel lines, i.e., the wake of the cavitation bubble becomes infinite. From a scientific point of view, we are interested in the instability problem of flow in the wakes and the physical properties of the fine structure of the interface between water and air. In addition, since the flow is open, there are several propagation speeds of sound. In the open flow, the fluid is a suspended media of water including the bubble.[2][3] Thus, the composite sound velocities have several values. Because the velocity in the interface layer changes from zero at the separating point to the outer flow speed, the two-phase flow is very unstable. Moreover, because these shapes can be obtained by a potential theory, we conducted interesting experiments to observe the fine structures of the shapes and to perform numerical simulations of them.[1]

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II. Experiment SETUP

In the cavitation water tunnel of Tamagawa university, we conducted the experiments in a water tunnel (50mmx100mm cross section) shown in Fig.1. The water tunnel has four-side-glasses, and 6mm diameter-50mm long cylinder is placed horizontally, so we can see both the upper interface and the lower interface in the gravitational fields. We used a high speed digital camera [Komeka DSX-240BC and a high power strobe flush [SLA-601 (15micro sec)]. And to see the interface and size of the area of water zone we used IR filter (KODAK-88A)

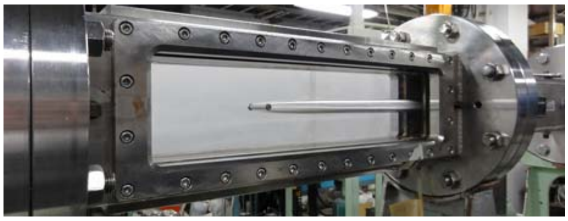

Fig.1 Tamagawa University Cavitation Tunnel

III. Experiment and Statistical Processing

1.The fine structures of both close-up photos and high speed observe the interface between water and vapor and bubbles in the dead water zone of the wake. Especially, the dead water zone a large dark region in low speed images are hard to observed since it is disturbed by sidewall bubbly wakes.

2.The three dimensional wakes of the sidewalls are observed.

3.The image processing of the high-speed photos and obtain the basic flow parameter such as the velocity and the density and the pseudo-porosity of the fluid.

4.Statistical treatment for the density gradient correlation and velocity correlation with images of high speed video cameras. Statistical variables are following:

$$<R_pR_q>(x,y)=<dDN_p(x,y))/dx_pdDN(x,y)/dx_q> \quad (1)$$

where DN is the digital number of the IR images (0 to 255)

$$\langle V_p V_q \rangle (x,y) = \langle dVp(x,y))/dxpdVq(x,y)/dxq \rangle (2)$$

Lagrange integration for the velocity (Projections) is

$$Vp(x,y) = \langle dXp(x,y))/dxp \rangle (3)$$

In Fig.3, 4 the invariant relation between the anisotropy tensor of the Reynolds stress representing the shear flow or boundary layer is similar to the anisotropy tensor of the density gradient correlation.[1]

In Fig.5, 6 the spatial distribution of the density correlation are shown. The asymmetry pattern is observed in Fig. 5, and the symmetry pattern is observed in the Fig.6. The patterns are distorted due to gravity. In Fig.7 the mean velocity distribution was estimated with a particle trace method.

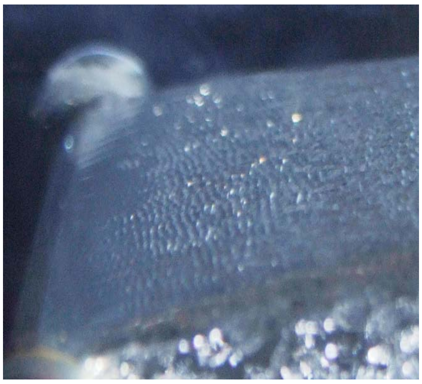

Fig.2 Capillary waves on the upper interface (Wave length:0.3mm)

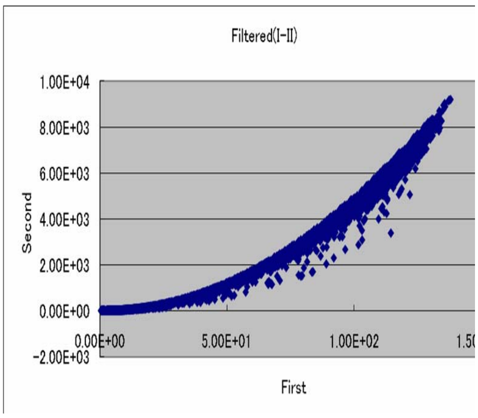

Fig.3 First and Second invariants

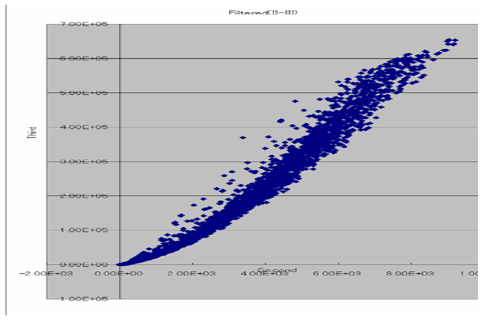

Fig.4 Second and third invariants

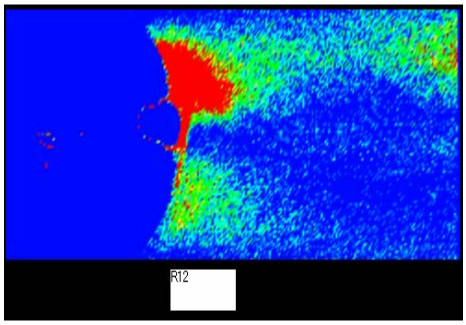

Fig.5 R12 (DGC-x-x) asymmetry

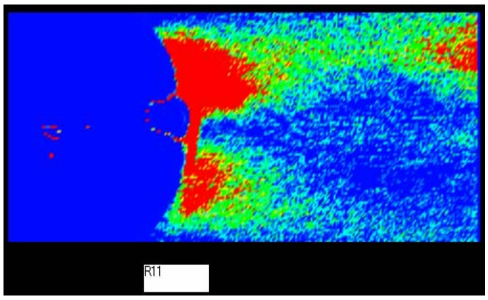

Fig.6 R11 (density-gradient-correlation-x-x)

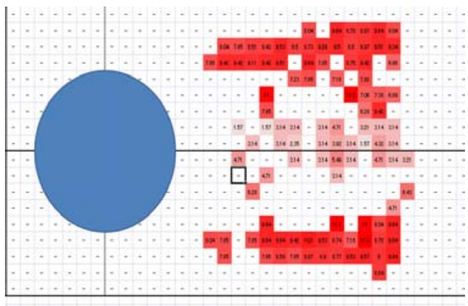

Fig.7 Velocity Distributions read from High-Speed Camera

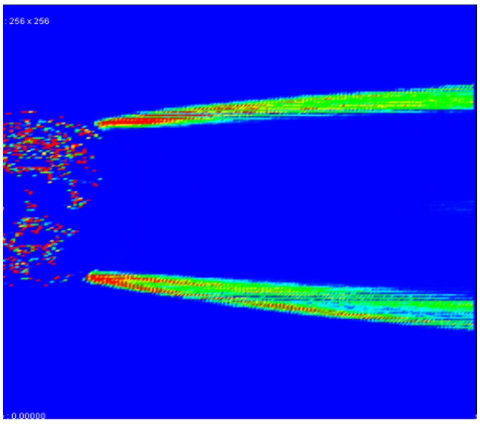

Fig.8 R11 (Symmetric)

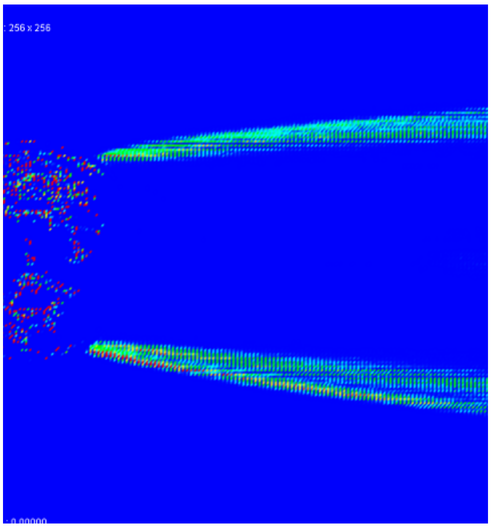

Fig .9 R12 (Symmetric) Density gradient (R11) blue part after the wake and red part after the wake shows the existence of the shear

IV. Wave propagation

Using the information from our observations, we set up problems using the well-known classical potential analyses of Milne-Thompson. If the upper fluid is lighter than the lower fluid, i.e., if a difference exists between the two fluids in the gravity field, and the gradient of the density is positive, then a wave is formed. We observed that the upper layer of the wake is water and the lower layer is vapor, so the gradient of density distribution is negative. Even in this situation, we observed ripples on both upper and lower surfaces. Because these results contradicted the potential theory, by conducting a numerical simulation of the compressible Navier-Stokes equations, we developed a thin sandwich potential model by adding a viscous effect that included the surface tension.

V. Results of Experiments

1) The high speed photos clearly show each bubble and the surface shape. The capillary waves started at a point 3mm from the cylinder (diameter 6mm), and they formed a two-dimensional wavy motion toward the downstream, the wave length of which was about 0.3mm. These were both gravity waves and capillary waves. (Fig.7)

2) The beams in this experiment passed through the outer flow zone and then through the dead water zone. The diffractive angle was almost the same. Thus, the fluid is more like a liquid and not a pure vapor gas. A picture of the dark region was recorded by using two high-speed cameras. We observed that massive air balls (0.3mm) drifted with a speed of 5m/sec to 8m/sec in the dead water zone. The velocity was estimated with the Lagrange path tracing method.

3) Three-dimensional horseshoe vortices were observed on the sidewalls (glass). The origins of these vertical helical vortexes were at the joint connecting the cylinder to the sidewalls. The wakes form towards the centerlines of the water tunnel, merge at the other side of the wake near the centerline, and go downstream. The three-dimensional wakes disturbed the real flow patterns slightly, but not enough to prevent photographing the inside of the test section. A mixed flow was observed near the sidewalls, shown in the photograph as focused and un-focused areas. The second and third invariants of the anisotropy tensor of the density gradient correlation express shear property as well as the Reynolds-stress anisotropy tensor. Fig. 11 shows the result of the classification used for remote sensing (maximum likelihood processing). There is a clear distribution of the air to water ratio in the wake. Because the surface porosity is about 0.3, we can evaluate the volume ratio at around 0.16. Thus, the density of the wake is nearly 840kg in 1000kg of water. Fig. 10 shows the instantaneous interface distribution if the two-dimensional flow simulation, which we assumed to be the flow field of the experiment, is the sequence of the surface porosity classified as a PCI Geomatica instantaneous surface pattern.

Fig.10. Bubbles in the dead water zone

The mixed two phase flow was observed near the sidewalls, in the photograph showed the focused and un-focused part. The second and third invariants of the anisotropy tensor of the density gradient correlation can also express the shear property as well as the anisotropy tensor of the Reynolds stress. In Fig. 11 the result of the classification used for the remote sensing (Maximum Likelihood processing) is shown. There is the clear distribution of the air to water ration in the wake. The surface porosity is about 0.3 and so, we can evaluate the volume porosity is around 0.16, thus the wake' density is nearly 840kg out of 1000kg water.

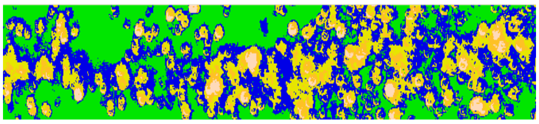

Fig.11 Classification Result

VI. Conclusion

The density gradient correlation can clearly express the interface of the shear layer. The second and third invariants of the anisotropy tensor of the density gradient correlation can express shear property as well as the Reynolds-stress anisotropy tensor. Our objective is to determine the nature of supercavitation. Therefore, our current project is an experiment on the asymmetric wakes of a cylinder, from which we may expect to learn more about the physical properties of interfaces, especially their fine structure.

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