A Study on Vortex Pair Interaction with Fluid Free Surface

K. H. Kim*, S. W. Kim**

Abstract

Today, the research to examine a fact that interaction between the air and the fluid free surface affects the steady state flow and air. We proved the interaction between vortex pairs and free surface on each condition that is created by the end of delta wings. Another purpose of this study is to investigate the effect of surface active material which can change the surface tension and we must consider when we refer to turbulent flow on surface tension. Therefore, this research examined the growth process of vortex pairs on condition of clean, contaminated free surface and wall after we made vortex pairs through counter rotating flaps. The results of this study suggest that vortex pairs in clean free surface rise safely but the vortex pairs in contaminated free surface and rigid, no slip is made secondary vortex or rebounding. However the secondary vortex in rigid, no slip is stronger than before, and we can find the vortex shape which roll up more completely. However, these will disappear by the effect of wall.

key word : Vortex pair, Surface tension, Turbulent flow, Rebounding, Secondary vortex

NOMENCLATURE

Fr : Froude number, $Fr = \Gamma/(g\delta^3)^{1/2}$
g : gravity acceleration [m/s^2]
Re : Reynolds number, $Re = \Gamma/\upsilon$
($\Gamma_{app} = 2\pi\,\delta_0 V_0$)
V_0 : propagation speed [m/s]
t : time [sec]
x, y, z : rectangular coordinate system

Letters of Greece

Γ : ccirculation [m^2/s]
(Γapp : apparent circulation)
δ : separation distance [m]
μ : absolute viscosity coefficient [g/sec]
υ : kinematic viscosity coefficient [m2/s]
π : surface pressure[dyne/cm]

* ; Professor of Dept. of Mechanical Eng. of Kyung Hee University, Gyeonggi, 449-701, Korea ,
E-mail : kimkh@khu.ac.kr
** : CO_2 Reduction and Sequestration R & D Center, K. I. E. R., Daejon, 305-343, Korea

1. Introduction

In fluid dynamics, the importance of vortices has been acknowledged and many researchers are trying to understand spatially expanded vortex flow. Among of the vortex flows, a vortex pair interacting with a free surface deforms the surface and can be rebounded from the surface under certain conditions.[1,2] However, a few experimental research works have been performed on the counter rotating vortex pair. Through the investigations, it is confirmed that surface active materials play an important role on the interaction of a counter rotating vortex pair with a free surface and many researches are being conducted to define the interaction process qualitatively and quantitatively. In the present investigation, a vortex pair generated at the bottom of the water tank moves toward a free surface and interacts. The interaction process is visualized using LIF. For the experiments, three different types of surface conditions are prepared; a clean free surface by distilled water, a contaminated free surface by surface active materials, and a rigid surface by acrilan plate.

2. Experimental apparatus and procedures

2.1 Experimental Apparatus

Vortex flow is generated by a pair of counter-rotating flaps and the figure 1 shows its schematic diagram. The generator is composed of stepping motor with gears, a pair of flaps and fluorescein die. As the flaps rotate, vortex sheets are generated from the flap tips, which are rounded to prevent from inducing any disturbances based on the fact that a laminar vortex generated from a sharp edge becomes turbulent much faster than a vortex from a round edge. The axis of the flaps are connected by a mylar sheet, which also helps to keep the generated vortex in laminar.[3]

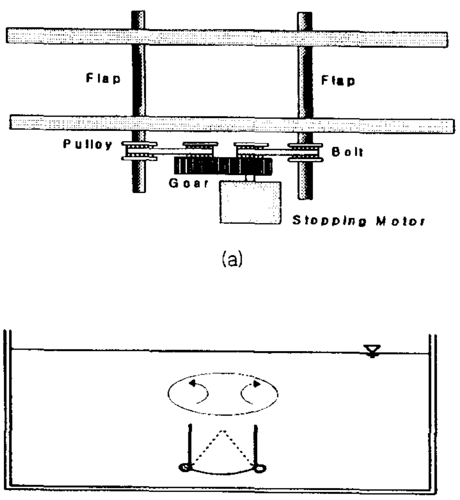

Fig. 1 Schematic of the vortex generator, producing vortices which propagate vertical the free surface : (a) top view, (b) front view

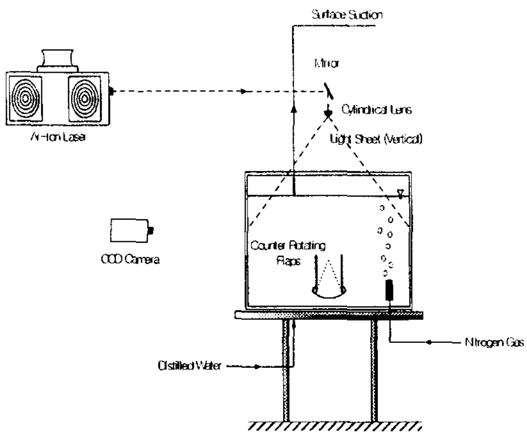

Fig. 2 Schematic diagram of the experimental setup for the flow visualization

Flow visualization is performed using the system shown as figure 2. The system is mainly composed by an argon-ion laser, CCD camera, and an image capture board.

2.2 Experimental procedures

2.2.1 Clean Free Surface

Surface tension is measured after the surface cleaning process using a ring surface tensiometer to confirm that the free surface is clean. The absolute error of the measurements is ±0.1dyne/cm. The measured surface tension of 72 dyne/cm. For a contaminated surface, stearic acid is used as surfactants. In order to dilute the surfactants and allow a measurable amount to be deposited on a given area, benzene is used as volatile solvents.

2.2.2 Rigid, No-Slip Boundary

When a vortex interacts with a rigid, no-slip boundary, a secondary vortex is generated from the boundary and the primary vortex is eventually rebounded from the boundary.[2] To simulate the rebounding process, an acrilan plate, 10x340x340mm is placed on the surface. Unlike the clean and the contaminated surfaces, a syringe is not allowed to access the flaps through the plate because any hole through the plate disperses laser light. Therefore, fluorescein die is injected from the both sides of the flaps.

2.2.3 Flow Visualization

LIF technique is utilized for flow visualization using fluorescein die(Rhodamine B) and an argon-ion laser(Ion Laser Technology, Model 5500A, 300 mmW). The die is injected prior to the flaps rotation. As the flaps are rotated towards each other a vortex sheet is shed from each tip, which rolls up to form a vortex pair. The vortex pair can be clearly observed in the light sheet by fluorescein die.

3. Results and Discussion

3.1 Clean Free Surface

Trajectory and propagation speed of a vortex pair interacting with a clean free surface or a contaminated free surface are measured by using seeding particles, which reflect laser lights in the water tank. The vortex interaction process is recorded at 30 frames/sec. The Reynolds number of these vortex pairs are calculated based on apparent circulation,

$$Re = \frac{(\Gamma_{app})}{\nu} \quad (\Gamma_{app} = 2\pi\delta_0 V_0)$$

The apparent circulation is determined by assuming the pair are point vortices in inviscid fluid. δ0 is the separation distance, υ is the kinematic viscosity coefficient, and V_0 is the propagation speed.[3] The maximum V_0 of figure 3 is 1.65 cm/sec with δ0 of 11.6 cm. The calculated Reynolds number is about 12,026 and the Froude number defined as $Fr=\Gamma_{app}/\sqrt{g\delta_0^3}$ is about 0.097, where Γapp is apparent circulation and δ0 is the spacing of the vortices before the interaction with the surface.

This low Froude number means that the free surface deformations by gravity are small during the interaction process of a vortex pair with a free surface. With $22{,}000 \leq Re \leq 66{,}000$ and $0.34 \leq Fr \leq 1.1$, the first surface deformations and the striations appear when the rising vortex pair has reached a distance beneath the surface comparable to the spacing between the vortices.[4]

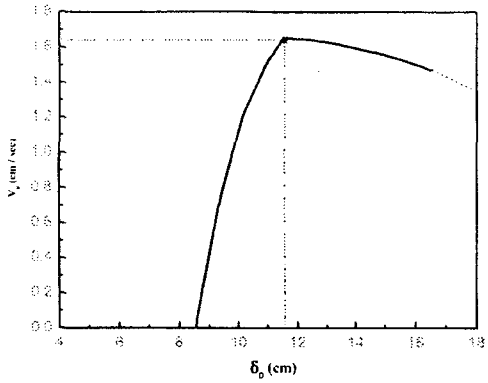

Fig. 3 Relationship between V_0 and δ_0 of the vortex pair

Figure 4 shows the interaction process of a vortex pair with the surface. In figure 4(a), the apparent centers of the vortices are approximately 8.6 cm beneath the free surface and the generated vortex pair is laminar and fully developed before the interaction. Figure 5(a) is the same image of figure 4(f).

Secondary vortices and rebounding are not observed in figure 5 because the vortices propagations along the surface are potential flows.

3.2 Contaminated Free Surface

Figure 6 show the interaction process of a right side vortex with the contaminated surface. The pictures are taken at every 0.5 second.

The pictures are apparently different from figure 4. Figure 6(f) shows a secondary vortices below the surface. The viscosity of the surface increases due to the stearic acid

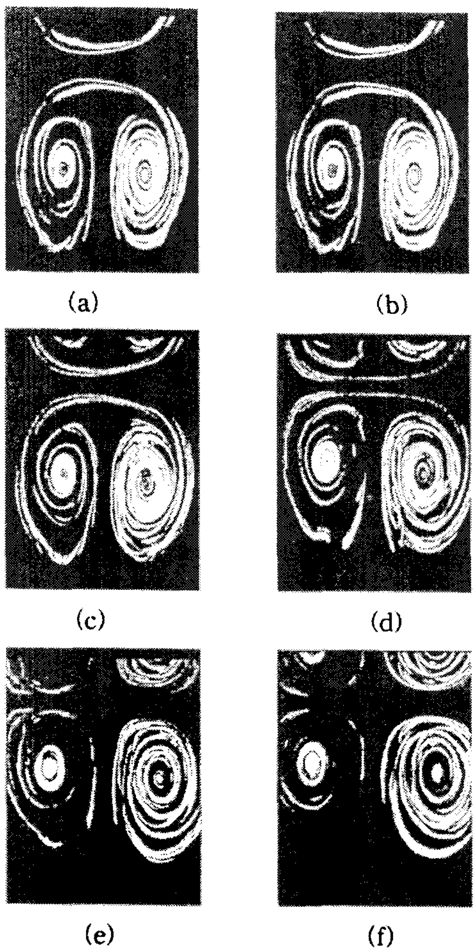

Fig. 4 Visualization sequence of vortex pair interaction with a clean free surface. Time increments between digital images are Δt=0.5s. Re=12.026 Fr=0.097

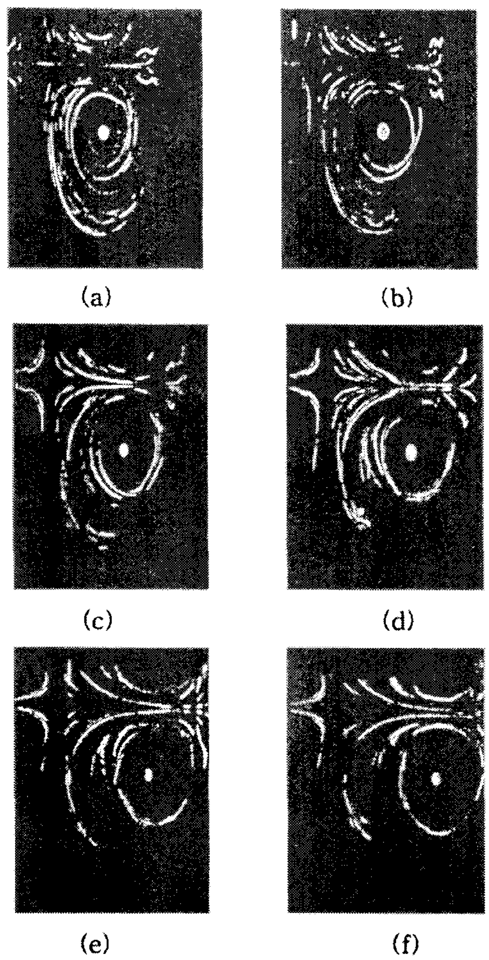

Fig. 5 Visualization sequence of right-hand vortex as it interaction with a clean free surface. Time increments between digital images are Δt=0.5s. Re=12.026 Fr=0.097

the increased viscosity generates opposite signed vorticity at the surface which can roll up into secondary vortices as shown in figure 6(g). As the secondary vortices grow up, the primary vortices are separated from the free surface. This separation process is generated by the stearic acid monolayer, which forms no-slip condition at the free surface. Figure 6(h) shows that the vortices are in transient from laminar to turbulent.

3.3 Rigid, No-Slip Boundary

The rigid, no-slip boundary is prepared to obtain experimental results to be compared to that of clean or contaminated surface. The rigid boundary does not allow any surface deformation by forming a no-slip condition.

The no-slip condition is similar but distinguishable to that of contaminated free surface.

The rigid boundary generates secondary vortices, which can be formed at the contaminated surface. This similarity can be confirmed by figure 6 and figure 7. However, secondary vortices from the rigid surface is much stronger than that of the contaminated surface as shown in figure 7(e).

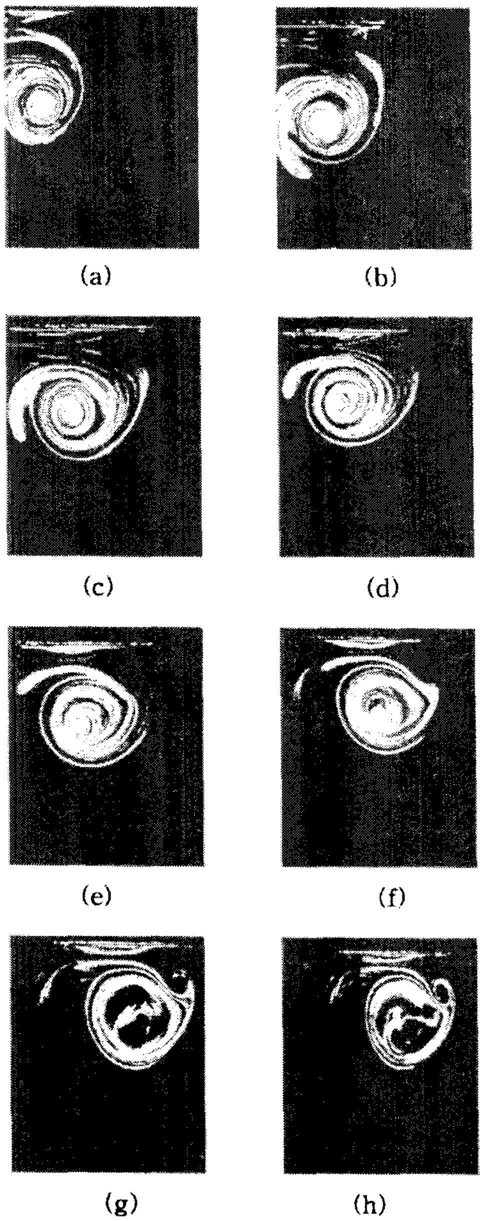

Fig. 6 Visualization sequence of right-hand vortex as it interacts with the surface covered by a stearic acid monolayer(π=62.5 dyne/cm). Time increments between digital images are Δt=0.5s. Re=12,026 Fr=0.097

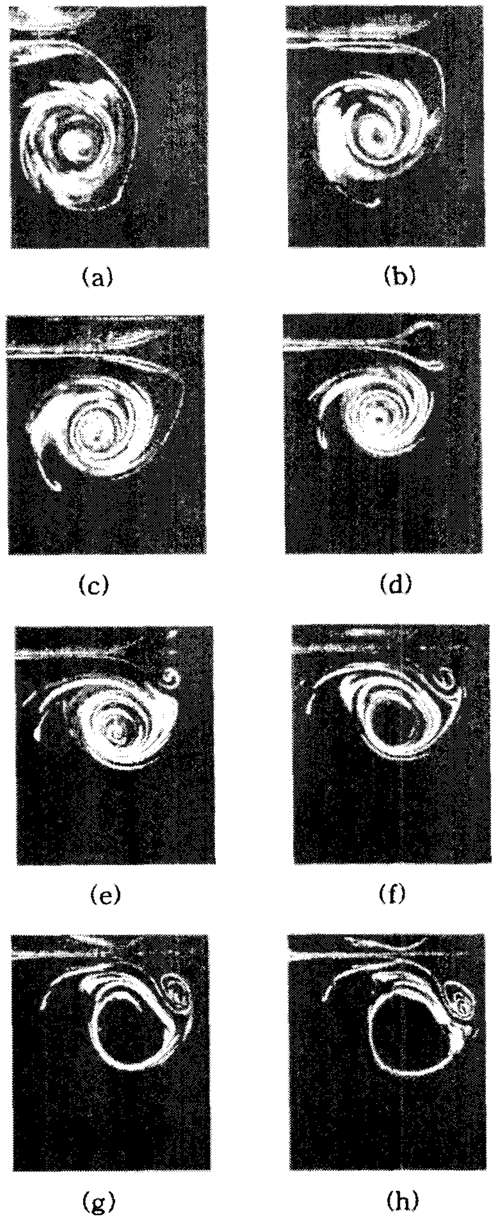

Fig. 7 Visualization sequence of right-hand vortex as it interacts with the a solid wall. Time increments between digital images are Δt=0.5s. Re=12,026 Fr=0.097

4. Conclusions

Experimental investigations have been performed on the vortex interaction with a clean, contaminate or rigid surface. Those three different types of the surface conditions results in different dynamic behaviors of a vortex pair which can be summarized as follows;

(1) Secondary vortices and rebounding of primary vortices are not generated at the clean surface. The primary vortices flow along the surface and are dissipated.

(2) It is confirmed that surfactants existing at the surface of river or ocean play an important role in the interaction process of a vortex with the surface. For the stearic acid case which has high surface shear viscosity, the surface generates opposite signed vorticity at the surface which can roll up into secondary vortices with approximately 1/5 of the circulation of the primary vortices. Those secondary vortices rebound the primary vortices from the surface. The rebounded primary vortices are dissipated earlier than that of the clean surface.

(3) The rigid plate shows a similar interaction process to the contaminated surface by generating no-slip condition. However, the secondary vortices are stronger than that of the contaminated surface by stearic acid.

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