EDDY SHEDDING FROM A CIRCULAR CYLINDER CLOSE TO A FREE SURFACE

Ichiro Kumagai
Faculty of Engineering
Hokkaido University
Kita13 Nishi8, Kita-ku, Sapporo, Hokkaido 060-8628 Japan
kumaton@eng.hokudai.ac.jp

Koji Oyabu, Takafumi Kushida, Yuji Taska, and Yuichi Murai
Faculty of Engineering
Hokkaido University
Kita13 Nishi8, Kita-ku, Sapporo, Hokkaido 060-8628 Japan

ABSTRACT

We have conducted laboratory experiments on the flow past a circular cylinder moving at a constant speed U_0 beneath an air-water interface. The vortex street and the free surface profile are visualized for Reynolds number ($Re=U_0d/\nu$) between 200 and 15,000 and for Froude number ($Fr=U_0/(hg)^{1/2}$) between 0.01 and 3.2 (d and h are the diameter of the cylinder and the distance between the top of the cylinder and the undisturbed water surface, respectively). At large Reynolds numbers ($>10^4$), the surface deformation becomes substantial in the downstream of the cylinder and the intermittent bubble injection by a jet-like flow is observed. We have also investigated variation of the Strouhal–Reynolds number relationship with the gap ratio ($a=h/d$) between 0.25 and 2.0, which shows the period of the vortex shedding becomes long when the gap ratio is small.

INTRODUCTION

Although our knowledge is extensive on the flow past a circular cylinder in infinite fluid (Bénard, 1908; Williamson, 1996; Zdravkovich, 1997; Scarano and Poelma, 2009), our understanding of the flow behaviour around the circular cylinder close to a free surface is relatively poor (Sheridan et al., 1997; Reichl et al., 2005) while this flow situation is common in practical applications such as submerged pipelines and marine constructions. The flow physics concerning the free-surface effect has not been clarified yet because extremely complicated phenomena, which are the interaction between the eddy and the free-surface wave, air entrainment into the water, and the bubble generation by the shear flow, are expected. Here we will show experimental results on (1) the effect of the gap ratio (cylinder depth h / cylinder diameter d) on the frequency f of the eddy shedding from a circular cylinder (Strouhal-Reynolds number relationship for $200 < Re < 10^4$) and (2) wave breaking and bubble generation by the interaction between a vortex street behind the cylinder and a free-surface wave for $Re > 10^4$.

EXPERIMENTAL SETUP

Figure 1 shows our experimental setup. The experimental tank (500 × 500 × 5000 mm) was filled with a tap water (350 mm in depth). A circular cylinder (diameter d=20 mm, span-wise length L=350 mm) was submerged in the water and towed by a linear servo actuator (N15SS, IAI) at a constant velocity U_0. A laser and a digital camera (CASIO, EX-F1) were attached to the linear servomotor actuator, which move

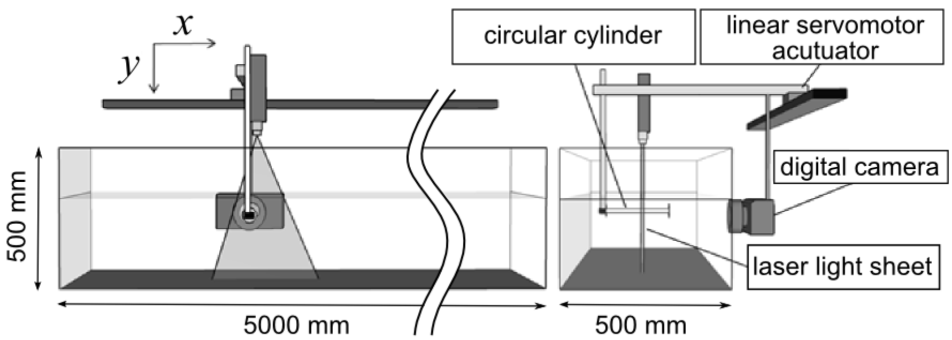

Figure 1. Experimental setup.

together with the circular cylinder. In order to observe the fluid motion around the 2-D cylinder, we added tracer particles (DIAION, Mitsubishi Chemical, specific gravity = 1.01, mean diameter ϕ~90 μm) in the water. We also seeded lighter tracer particles (Flo-Beads, Sumitomo Seika, specific gravity = 0.919, mean diameter ϕ~180μm) to visualize the air-water interface. The vortex street and the free surface profile are visualized for Reynolds number ($Re=U_0 d/\nu$) between 200 and 15,000 and for Froude number ($Fr_h=U_0/(hg)^{1/2}$) between 0.01 and 3.2 where h is the distance between the top of the cylinder and the undisturbed water surface.

EXPERIMENTAL PARAMETERS

For the description of the flow dynamics of a cylinder moving at a constant speed U_0 in an infinite fluid, Reynolds number is defined as

$$Re = U_0\, d\, /\, \nu \qquad (1)$$

where d and ν are the characteristic length scale (e.g. diameter of the cylinder) and kinematic viscosity of the fluid (water), respectively.

Since our cylinder moves beneath the water surface, the flow behavior should also be influenced by the following non dimensional parameters.

- Froude number, $Fr = U_0 / (gh)^{1/2}$ (2)

where g and h are gravity acceleration and water depth, respectively.

- Water depth ratio, $a = h / d$. (3)

- Viscosity ratio, $\gamma = \nu_{air} / \nu$ (4)

where ν_{air} is the kinematic viscosity of the air.

The experimental conditions in our study are shown in Table 1. Since we use the air-water system, the kinematic viscosity ratio is constant (~17) through our experiments.

Table 1. Experimental conditions

Re	200 ~ 15000
Fr	0.01 ~ 3.2
a	0.25 ~ 2.0

RESULTS AND DISCUSSION

Figure 2 shows snapshots of circular cylinders at different Reynolds number. As the towing velocity U_0 increases (Re increases), the magnitude of the water-surface depression w behind the moving cylinder increases. The waveform behind the cylinder becomes unstable and breaking wave occurs on the forward face of the wave (Figure 2d, Re > ~10^4). Once the breaking wave occurs, the atmospheric air is entrained and small bubbles are created. Figure 3 shows the depression w, which was measured from the image data of the water surface profile, as a function of U_0 at varying depth h. For small disturbance of the air-water interface, open symbols in Figure 4, the depression w can be described at first order as the kinematic energy of the flow ($\rho U_0^2/2$) is transformed into the potential energy ($\Delta\rho g w \sim \rho g w$):

$$w = U_0^2/2g. \qquad (5)$$

As shown in Figure 3, the experimental results have a good agreement with Eq. (5) for small w (w < ~10 mm, U_0 < ~400 mm/sec). However, the discrepancy between the measured data and Eq. (5) is apparent when the breaking wave with bubble generation occurs (closed symbols in Figure 3). With the increase of U_0, the depression w approaches a constant value which seems to depend on h.

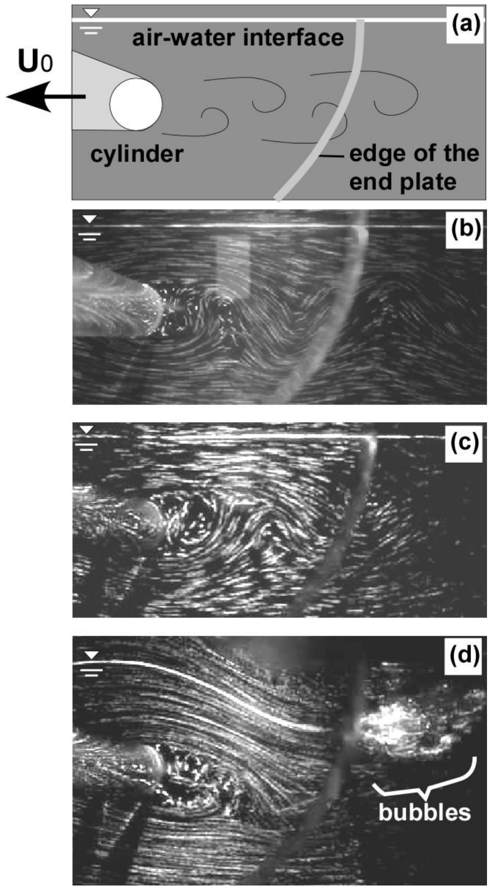

Figure 2. Vortex street exhibited by motion of tracer particles (a = 1.0): (a) experimental configuration; Re~ (b) 600, (c) 3000, (d) 12000.

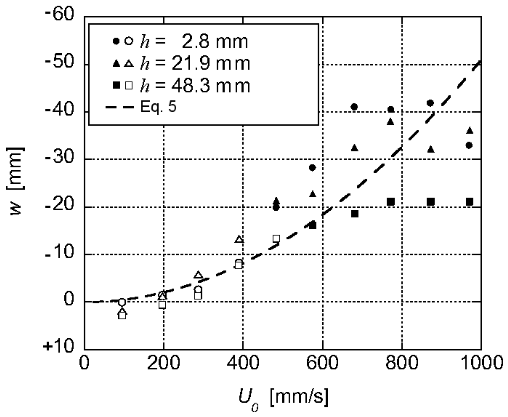

Figure 3. Water surface depression w by a moving cylinder as a function of U_0 at different water depth h. Open and closed symbols denote non-existence and existence of breaking wave with bubble generation, respectively. The broken line represents Eq. (5) : $w = U_0^2 / 2g$.

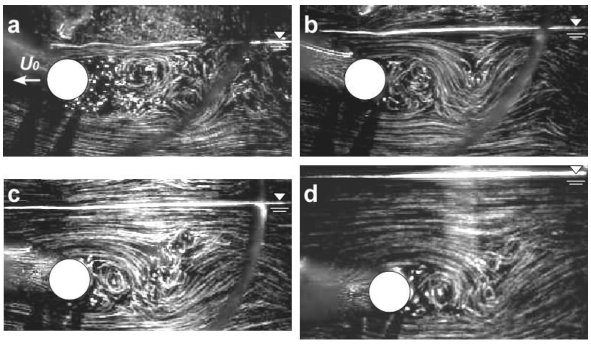

Figure 4. Photos of the flow past a circular cylinder beneath a free surface at Re~3000; the gap ratio a= (a) 0.25, (b) 0.5, (c) 1.0, (d) 2.0.

Effect of the free surface on the *Strouhal-Reynolds* relationship for 200 < *Re* < 10^4

Figure 4 shows variation of the flow pattern with the gap ratio. Kármán vortex street is shown by path lines obtained from overlapping instantaneous images. In these images, a white circle and an arrow indicate the circular cylinder and the towing direction of the cylinder, respectively. In Figure 4b-d, two rows of vortices are regularly shedding from the either side of the cylinder. The flow pattern is similar to the unbounded case except for a=0.25. In the shallower case (Fig. 4a, gap ratio a =0.25), the vortex appears on far side from the cylinder and the vortex shedding is not fully developed. The vortex structure of the top row, which is close to free surface, is small. In order to investigate the influence of the free surface on the vortex structure, a relationship between Re and Strouhal number ($St=fd/U_0$, where f is the frequency of eddy shedding) is shown in Figure 5. When a bluff body moves in an unbounded fluid, Kármán vortex street is generated behind the body over a wide range of Re. It is well known that the St is about 0.2 in the range of $5\times10^2 \leqq Re \leqq 3\times10^5$ for a circular cylinder. The St number in our experiments is also about 0.2 as the previous studies except for the case of a=0.25 which shows smaller St. Especially St is significantly small when the Re is smaller than 10^3. This phenomenon suggests that proximity to the free surface results modification of the velocity boundary layer over the cylinder. This yields the eddy shedding on one side is delayed and the resultant frequency becomes small.

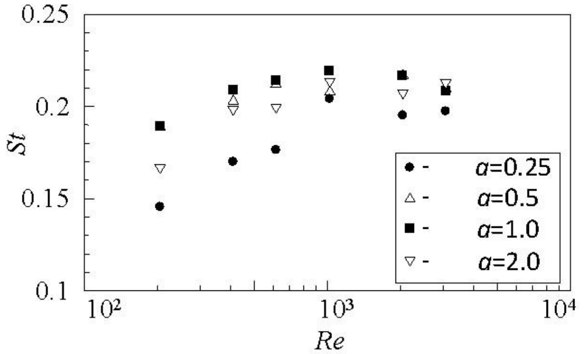

Figure 5. Variation of the Strouhal - Reynolds number relationship with gap ratio a.

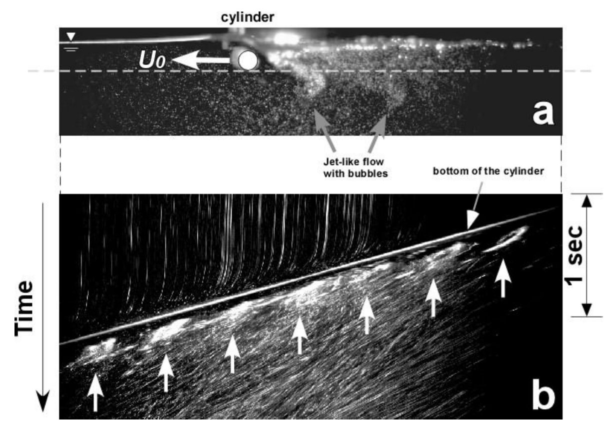

Figure 6. Bubble injection by a jet-like flow (Re~9000, a~0.25): (a) original image; (b) a spatio-temporal slice at the bottom of the cylinder (a broken line in Figure 5a) generated from video frames. White arrows show the light scattering from bubbles injected by the jet-like flow from the air-water interface.

Intermittent bubble injection by eddy shedding for 10^4 < *Re* < 1.5×10^4

As Re increases, wave breaking with air entrainment behind the moving cylinder occurs (Figure 2d). As shown in Figure 6a, air is injected like jet flow. Figure 6b shows a spatio-temporal slice at the bottom of the cylinder in experimental image. From this figure, intermittent air injection by the jet like flow is observed. Because the frequency of the intermittent air entrainment is similar to the frequency of the

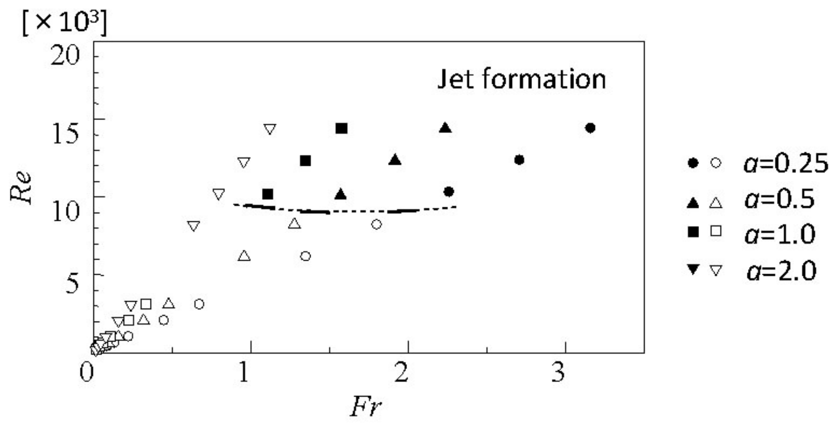

Figure 7. Regime diagram for bubble injection by a jet-like flow. The closed symbols show that the jet-like flow with bubble generation is observed in our experiments

eddy shedding, interference between the vortex shedding and the air entrainment is expected. The oscillation of the eddy shedding affects the waveform behind the cylinder. The slope of the forward face of the wave also oscillates and breaking wave with bubble injection occurs intermittently (Figure 6b).

Figure 7 shows regime diagram for the bubble injection by the intermittent wave breaking. The threshold of bubble formation by breaking wave depends on *Re*, *Fr*, and normalized depth of the cylinder ($a=h/d$).

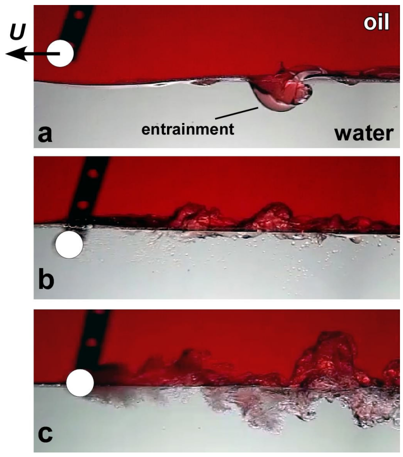

Figure 8. Shadow image by the back light illumination. U_0 = (a) 1590, (b) 1297, (c) 1830 mm/sec. The diameter of the cylinder is 20 mm. The oil layer is dyed red.

Entrainment by vortices shedding from the cylinder close to a liquid-liquid interface

Figure 8 shows flow behaviour around a towed cylinder close to a liquid-liquid interface (an oil-water interface). The free surface is deformed by the vortices behind the cylinder. Because two rows of vortices are regularly generated from the either side of the cylinder, the intermittent entrainment around the liquid-liquid interface was also observed in our experimental conditions.

CONCLUSIONS

Laboratory experiments on the flow past a cylinder close to a free surface show that *St* number becomes small when the gap ratio a is small enough (a=0.25). The vortex shedding on one side should be delayed if the cylinder depth h is comparable to the thickness of the velocity boundary layer on the cylinder. For higher *Re* number ($Re > 10^4$), deformation of the free surface becomes significant and air entrainment into the water is observed. The free-surface profile is affected by the eddy streets, which causes intermittent bubble injection.

ACKNOWLEDGEMENTS

This work was supported by New Energy and Industrial Technology Development Organization (NEDO) of Japan (grant no. 08 B 36002).

REFERENCES

Bénard, H.. 1908, Formation de centres de giration à l'arrière d'un obstacle en movement, Comptes Rendus Académie des Sciences, 147, pp 839-842.

Reichl, P., Hourigan, K., and Thompson, M.C., 2005, Flow past a cylinder close to a free surface, *Journal of Fluid Mechanics*, 533, pp 269-296.

Scarano, F. and Poelma, C., 2009 Three-dimensional vorticity patterns of cylinder wakes, *Experiments in Fluids*, 47, pp 69-83.

Sheridan, J., Lin J.-C., and Rockwell, D., 1997, Flow past a cylinder close to a free surface, *Journal of Fluid Mechanics,* 330, pp 1-30.

Williamson, C.H.K., 1996, Vortex dynamics in the cylinder wake, *Annual Review of Fluid Mechanics*, 28, pp 477-539.

Zdravkovich, M.M.,1997, Flow around circular cylinders. vol. 1: fundamentals, p.692, Oxford Univ. Press.