On the motion of a falling circular cylinder in flows after water entry

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ABSTRACT

This paper reports an experimental investigation on the motion of a circular cylinder after it horizontally enters into a water flow with a certain slamming speed. A smart cylinder-releasing mechanism is designed to enable repeatable release of the cylinder. A high-speed camera is used to record the cylinder's motion. The effects of three factors are investigated, including the cylinder-to-water density ratio, water speed and slamming speed of the cylinder. Data for several cases with either a solid cylinder or a hollow cylinder are obtained and compared. Variations of both horizontal and vertical displacements against these factors are presented and analyzed. It is found that the trajectories of the hollow cylinder collapse at the initial stage of submerging in water when the velocity ratios are the same.

Keywords: freely falling circular cylinder, high-speed camera, water tunnel

1. INTRODUCTION

An object falling into water results in complex flow phenomena with perturbation in the wake [1, 2]. In return the perturbation also exerts an impact load on the object so that the object's motion changes. Mahadevan et al. [3] performed experiments on freely falling rectangular strips and indicated the effects of several factors on the associated flow separation and vortex shedding. Motion of freely falling parallelograms cards coupled with tumbling-helical motions is presented by Varshney et al. [4], in which aerodynamics forces and torques on the cards are discussed to explain the interesting phenomenon.

A cylinder freely falling into calm water has been extensively studied by many researchers in the past few years [5-8]. Abelev et al. [9-11] conducted a series of experiments on full-scale instrument cylinders and discussed the hydrodynamics characters. Interesting results such as the critical depth for cylinder free falling motion and apparent periodicity in cylinder motions were obtained. A computational model was developed by Mann et al. [12] to predict the motion of cylindrical mines impacting on water surface and then dropping in water toward the sea bottom. Hydrodynamic effects due to the water impact and viscous drag due to flow separation and vortex shedding were taken into account. Wei and Hu [13] experimentally studied complex hydrodynamics of a circular cylinder horizontally entering into water at low Froude numbers. They focused on the three-dimensional cavitation effect on the water entry. Horowitz and Williamson [14] studied the dynamics of a cylinder rising or falling freely through a fluid. More recently, developments for interaction of two freely falling cylinders [15] were also reported.

Objects freely falling into non-zero-speed water flows is also interesting but is seldom studied. Starting from a very simple case, therefore, this research aims to investigate the motion of a circular cylinder after it horizontally enters into flowing water. Since the initial status of the cylinder is very important, a smart releasing mechanism is designed and developed to ensure repeatable release of the cylinder. The experiments are conducted in a low-speed water tunnel. A high-speed camera is used to record the cylinder's motion. The effects of various factors are investigated, including the cylinder-to-water density ratio, slamming speed of cylinder and water speed.

2. TEST RIG

Since the effect of water speed is the focus of this investigation, the present experiment is performed in a water tunnel with a test section of 0.45m (W) × 0.45m (H) × 1m (L). The maximum achievable water speed is 0.2 m/s. Two aluminum cylinders of diameter D = 20 mm and length L = 100 mm are used: one is solid with a cylinder-to-water density ratio $R_\rho = \rho_c / \rho_w = 2.7$ and the other is hollow one with a density ratio $R_\rho = \rho_c / \rho_w = 1.26$, where ρ_c is the density of cylinder and ρ_w is water density.

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To facilitate repeatable release of the cylinders, a smart releasing mechanism is designed and developed. A schematic of the releasing mechanism is shown in Figure 1, which consists of five components, i.e., a cylinder holder, an electromagnet system, springs, linear guides and the supporting structure. The cylinder holder consists of two pairs of clamps that can hold the cylinder from its two ends. The clamps are carefully adjusted to ensure the horizontal release of the cylinder with minimum disturbance. During the tests the cylinder is held in such a way that its axis is vertical to the direction of water flow. At the beginning of each test the cylinder is held with the force applied by the electromagnet system, which includes an electromagnet (maximum pull force of 53 N at current 100mA and 24V DC), a switch and a DC power supply. The releasing of the cylinder is realized by the switch-off of the electromagnet system and the pulling of the two springs. Initially the springs are extended sufficiently so that the cylinder releasing can be done in a very short time.

Images of the experiment are acquired with a high-speed camera FASTEC HiSpec1 (up to 506 frames per second with a resolution of 1280×1024) from one side of the water tunnel. The camera is positioned in such a way that its central line is parallel to the still water surface. It is also synchronized with the smart releasing mechanism, so that the image recording can start immediately after the releasing starts. Images of the cylinder are taken and analyzed using MotionBLITZ Director2 software to study the motion details.

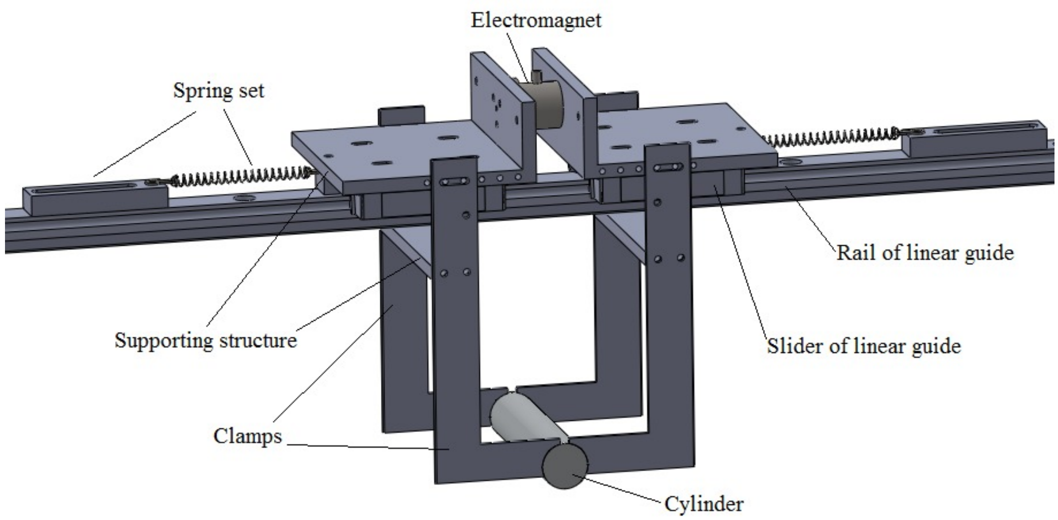


Figure 1. Experimental releasing mechanism

3. EXPERIMENT RESULTS

Objects entering water leads to very complicated phenomena, which however are not the focus of the current study. Instead, the research focus is on the cylinder's motion after it moves just below the water surface. More specifically, this research looks at how the slamming speed and water speed affect the motion of the cylinder in a very short time (80 ms) after it moves into the water. In the present experiments, two slamming speeds (V_c) are used, i.e., 0.5 m/s and 1 m/s, which are defined as the speed of the cylinder when it just arrives the water surface and are determined by the releasing height. The water speed (V_w) in the water tunnel varies from 0 to 0.165 m/s. Therefore a velocity ratio can be defined as $R_v = V_c/V_w$. The characters of the two cylinders are shown in Table 1 and the test cases in Table 2. To reduce the influence of possible disturbance introduced during the releasing, each case is repeated for 3~5 times and the best one is picked for analysis.

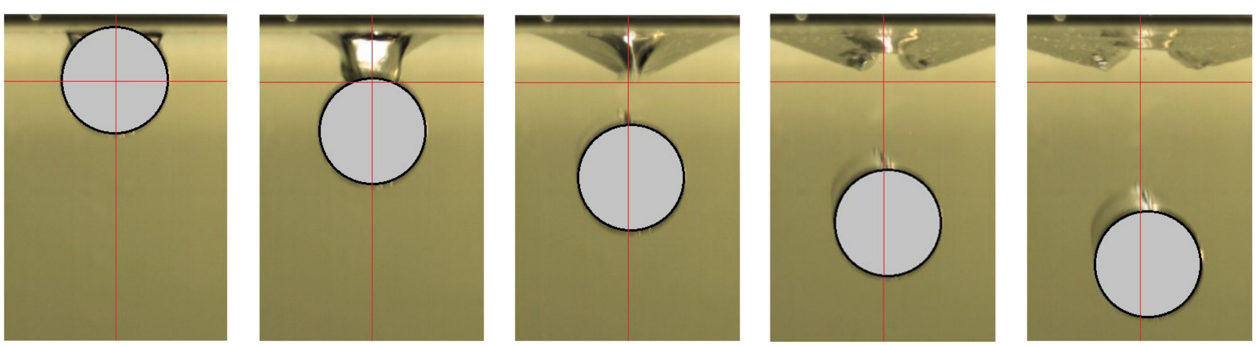
Table 1. Characters of the cylinders

Characters	Hollow Cylinder	Solid Cylinder
Diameter (mm)	20	20
Length (mm)	100	100
Density Ratio	1.26	2.7
Slamming Velocity (m/s)	0.5, 1	0.5

Table 2. Experimental cases

Case No.	Cylinder type	Slamming Velocity V_c (m/s)	Water Velocity V_w (m/s)
1	Hollow	0.5	0.05
2	Hollow	0.5	0.1
3	Hollow	0.5	0.165
4	Hollow	1	0.05
5	Hollow	1	0.1
6	Solid	0.5	0.1
7	Hollow	0.5	0

As an example, a time sequence of snapshots for Case 1, i.e., the hollow cylinder at V_c = 0.5 m/s and V_w = 0.05 m/s, are shown in Figure 2. The solid lines marked in the figure are used as a reference for displacement calculation. Evident trajectory offset from the initial vertical centerline can be observed. Since the camera is fixed during the test, there seems a three-dimensional effect after the cylinder falls a distance away from the water surface. At the first 20 ms, there is an obvious cavitation above the cylinder. As the cylinder moves down, the cavitation breaks down and leads to fluctuation on free surface (t = 40 ms). Due to the water flowing from left to right, waves on free surface get a horizontal offset relative to the cylinder's initial position (t = 60 ms and t = 80 ms).



(a) t=0 ms (b) t=20 ms (c) t=40 ms (d) t=60 ms (e) t=80 ms

Figure 2. Snapshots of the falling hollow cylinder for Case 1.

The variation of the horizontal displacement of the hollow cylinder with respect to time is plotted in Figure 3. It is found that the horizontal displacement increases as the water speed increases, from 0.05 m/s to 0.1 m/s, and subsequently to 0.165 m/s (cases 1, 2 and 3). At the same water speed, the horizontal displacements are very close even with different slamming speeds (compare cases 1 and 4, or 2 and 5). It is further found that, at the same water speed, the horizontal displacement at $V_c = 0.5$ m/s is greater than that at $V_c = 1$ m/s in the first 40 ms while an opposite trend is observed from 50 to 80 ms. The possible reason for this shift is that, at the initial stage of submergence, the slamming force between the cylinder and water is approximately proportional to the slamming speed square. Therefore the cylinder with a higher slamming speed causes greater cylinder-water interaction, resulting in a horizontal speed slower than the water speed, whereas the cylinder with a smaller slamming speed catches up with the water speed more easily and moves downstream at the water speed. After the slamming process completes, the low-pressure wake formed behind the higher-slamming-speed cylinder during the slamming process "pulls" the cylinder forward and hence causes the cylinder accelerating and reaching a speed higher than the water speed. In addition, as shown in Figure 4, at the same water speed the horizontal displacements of cylinders with different slamming speed or density ratio collapse in the first 60 ms and differ a little afterwards. This result reveals that the horizontal displacement is neither sensitive to slamming speed (compare case 2 and 5) nor to density ratio (compare case 2 and 6).

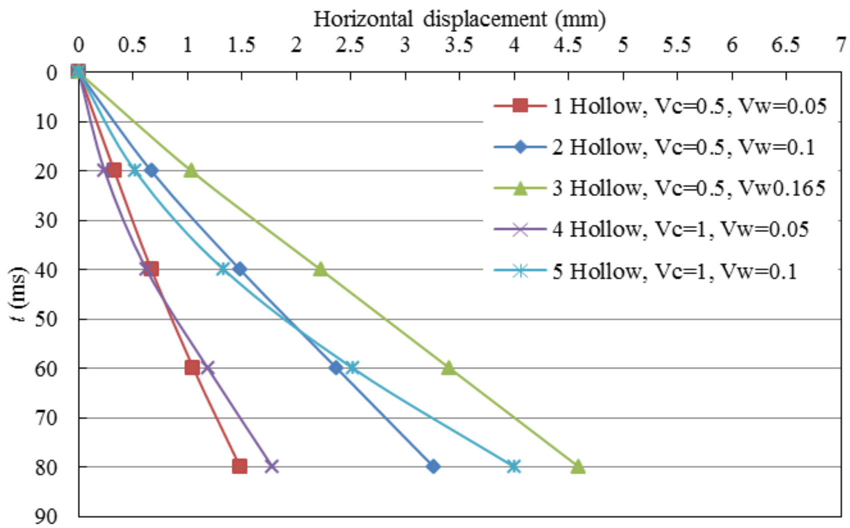


Figure 3. The horizontal displacement of hollow cylinder increases as the water speed increases.

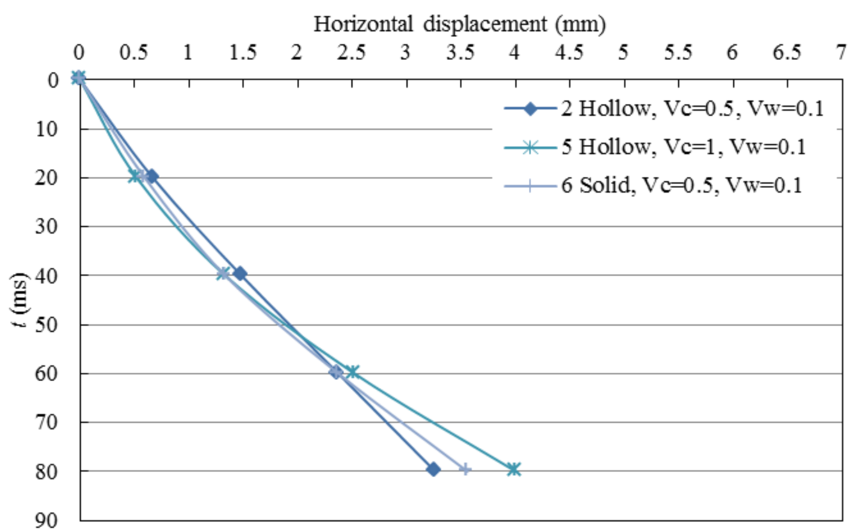


Figure 4. Horizontal displacement turns out to be aligned for both hollow and solid cylinder with the same water speed.

The time histories of vertical displacements for all the seven cases are plotted in Figure 5. It reveals the water speed has little effects on the vertical displacement (cases 1, 2 and 7 at $V_w = 0.5$ m/s, or cases 4 and 5 at $V_w = 1.0$ m/s) for the hollow cylinder. At the same water speed, the curves for the hollow cylinder agree well with each other. Although the initial conditions including the water speed and slamming speed for the hollow and solid cylinders (cases 2 and 6) are the same, these two cylinders perform differently in the vertical displacement due to different density ratio. The solid cylinder shows a much higher displacement with a higher slope of the curve that presents velocity of the cylinder.

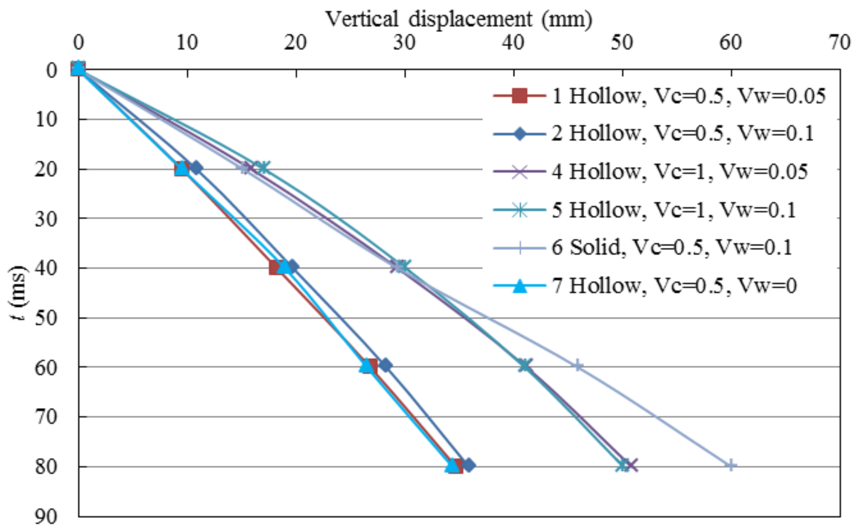


Figure 5. Vertical displacement for hollow and solid cylinder coincides with each other at the same slamming speed.

The trajectories, which are the combination of horizontal and vertical displacements, are also presented for the falling cylinders. Experimental results for the hollow cylinder suggest that the horizontal offset of trajectory from the vertical reference plane increases with the decreasing of velocity ratio R_V as indicated in Figure 6. The higher the water speed or the slamming speed, the higher this offset. In addition, when the velocity ratio is the same for the hollow cylinder (cases 1 and 5), i.e., $R_V = 10$, the trajectories collapse at the initial stage. Due to the higher density ratio, the solid cylinder moves a further distance away from the water surface than the corresponding hollow cylinder at the same water speed and slamming speed (cases 2 and 6).

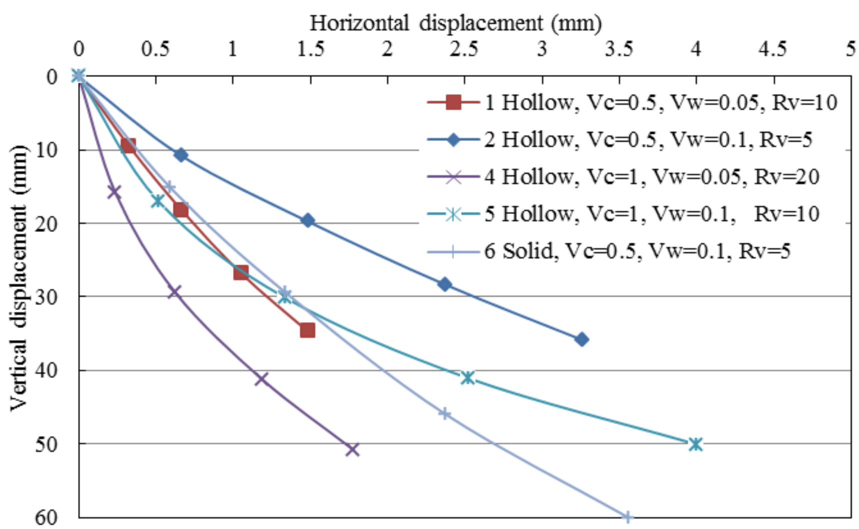


Figure 6. Trajectories varies obviously with variation of velocity ration and collapse at the initial stage if cylinder runs at the same velocity ratio

4. CONCLUSION

The displacements and trajectories of freely falling circular cylinders after the water entry are experimentally studied in a low speed water tunnel. A smart cylinder releasing mechanism is designed for this study, which ensures the repeatable release of the cylinder. A solid cylinder ($R_\rho = 2.7$) and a hollow cylinder ($R_\rho = 1.26$) are used in the tests. Effects of water speed and slamming speed of cylinder on the motion of cylinder are investigated. Experimental results indicate that the horizontal displacement is neither sensitive to slamming speed nor to density ratio. In addition, the water speed has little effects on the vertical displacement of the cylinder for a given density ratio. Furthermore, it is found that the offset of the cylinder trajectory increases with the decreasing of velocity ratio R_v and the trajectories collapse at the initial stage when the velocity ratio is the same for the hollow cylinder.

REFERENCES

[1] Belmonte, A., Eisenberg, H., Moses, E. 1998. From flutter to tumble: Inertial drag and Froude similarity in falling paper. Phys Rev Lett 81:345-348

[2] Zhong, H., Lee, C., Su, Z., Chen, S., Zhou, M., Wu, J. 2013. Experimental investigation of freely falling thin disks. Part 1. The flow structures and Reynolds number effects on the zigzag motion. J Fluid Mech 716:228-250

[3] Mahadevan, L., Ryu, W. S., Samuel, A. 1999. Tumbling cards. Phys Fluids 11:1-3

[4] Varshney, K., Chang, S., Wang, Z. J. 2013. Unsteady aerodynamic forces and torques on falling parallelograms in coupled tumbling-helical motions. Phys Rev E 87:53021

[5] Chu, P. C., Giles, A. F., Fan, C., Lan, J., Fleischer, P. 2002. Hydrodynamical characteristics of a falling cylinder in water column. Adv Fluid Mech 32:163-182

[6] Chu, P. C., Gilles, A., Fan, C. 2005. Experiment of falling cylinder through the water column. Exp Therm Fluid Sci 29:555-168

[7] Fernandes, P. C., Ern, P., Risso, F., Magnaudet, J. 2005. On the zigzag dynamics of freely moving axisymmetric bodies. Phys Fluids 17:98-107

[8] Jayaweera, K. O. L. F. 1965. The behaviour of freely falling cylinders and cones in a viscous fluid. J Fluid Mech 22:709-820

[9] Abelev, A. V., Valent, P. J., Plant, N. G., Holland, K. T. 2003. Evaluation and quantification of randomness in free-fall trajectories of instrumented cylinders. OCEANS 2003. Proceedings, pp. 2355-2365

[10] Abelev, A. V., Valent, P. J., Holland, K. T. 2007. Behavior of a Large Cylinder in Free-Fall Through Water. Ieee J Oceanic Eng 32:10-20

[11] Holland, K. T., Green, A. W., Abelev, A., Valent, P. J. 2004. Parameterization of the in-water motions of falling cylinders using high-speed video. Exp Fluids 37:690-700

[12] Mann, J., Liu, Y., Kim, Y., Yue, D. K. 2007. Deterministic and stochastic predictions of motion dynamics of cylindrical mines falling through water. IEEE Journal of Oceanic Eng 32:21-33

[13] Wei, Z., Hu, C. 2014. An experimental study on water entry of horizontal cylinders. J Mar Sci Technol

[14] Horowitz, M., Williamson, C. H. K. 2006. Dynamics of a rising and falling cylinder. J Fluid Struct 22:837-843

[15] Ern, P., Brosse, N. 2014. Interaction of two axisymmetric bodies falling side by side at moderate Reynolds numbers. J Fluid Mech 741