Surface Condition of Solid in Splash Formation

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The Fluid-Structure Interaction (FSI) is one of the most popular topics in the computational mechanics. It covers a wide range of phenomena of scientific and engineering fields such as vehicle, medicine, civil engineering and construction, agriculture, forestry, disaster prevention, music, sports, etc. The vibration of structure caused by the Kármán's vortex street has been studied for many years, which is a locking phenomenon caused by the vortex street behind a spherical cylinder [1]. The FSI study has contributed to the sport engineering: the improvement of the movement form of swimmer [2-3]. Regarding the sound of musical instruments, the vibration of a musical instrument and the circumference air and the pronunciation mechanism of an air lead of pipe organ or flute have been studied [4-6].

The vortex and the exfoliation occur when a solid or structure moves in fluid, which often result in the destruction, the noise, the stall of an airplane or the drag of a vehicle, and the various studies have been performed: the effect by the surface unevenness such as a turbulator, a vortex generator, a tripping-wire, a riblet of wing, and dimples of golf ball [7], the drag reduction of ship by the micro bubble [8], the effect of deformation by an elastic body [9], the relation of vortex and vibration [10], etc.

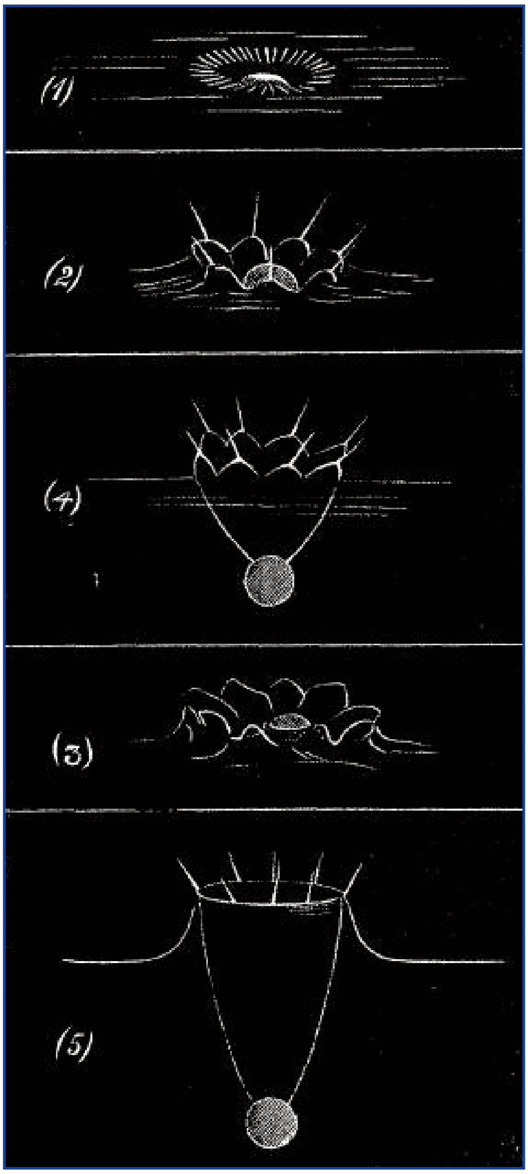


Figure 1: *Observation of the splash by a ball [13]*

"... in the dive ... it is important to jump into water pool after a swimmer wipes body well in order to get the high score."

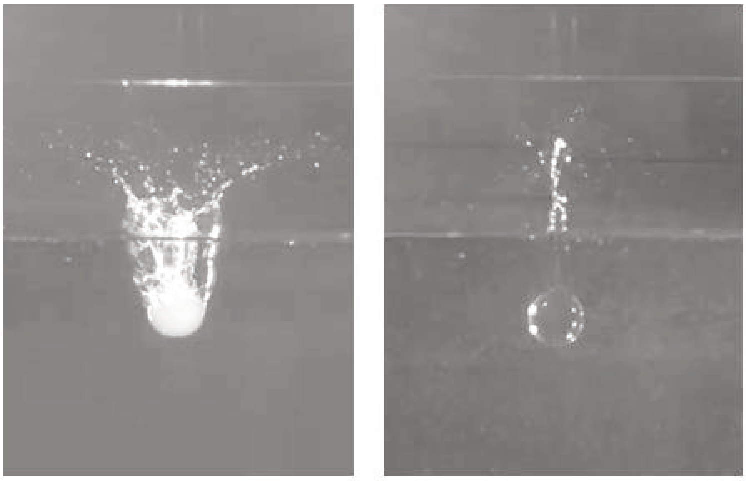
It is well known that the surface condition, the roughness of surface or the uneven shape of the solid surface gives some influence on the flow fields and the movement of the solid as seen in the case of the dimple of a golf ball [11]. In the most of the FSI studies, however, the wall of the solid or the structures is assumed to be as non-slip condition in numerical simulation. It is not a realistic assumption. For example, creatures living in water such as fish and amphibians have a slimy mucus skin, whose principal ingredient is a hydrogel known as mucin [12]. Furthermore, since the inner wall of the digestive organs or the blood vessel has a slippery surface, it seems important to take the characteristics of such slippery surface into consideration in numerical simulation.

Experimental observation of the splash of a ball, which plunged into water was performed by Worthington [13], *Figure1*. He studied the influence of the state of the surface of a ball on the splash. With the dry smooth ball, the size of the splash became small. With the ball made coarse with the sandpaper or the wet ball, it became a big crown-like splash. It shows that, in the dive game of swimming, since splash will become large if a swimmer jumps into water pool without wiping the body well or with swimming suit wet, the score becomes disadvantageous. Thus, it is important to jump into water pool after a swimmer wipes body well in order to get the high score.

The experimental results by a high-speed camera of a splash formed by a sphere impinging on water surface are shown in Fig. 2 [14], comparing the primary splash formed by a hydrogel sphere (Fig. 2A) with that by an acrylic sphere (Fig. 2B), where the primary splash means the splash, which rises right after an object plunging. The primary splash formed by the hydrogel sphere is a kind of the crown-type. On the other hand, the acrylic sphere creates the column type primary splash. The splashes are considered to be formed by the dynamics of the film-flow [14], which is a thin water flow around a sphere surface and generated immediately after the sphere impacts the water surface. The difference between the formation processes of *Figures 2A & 2B* is due to the existence of the film on the sphere surface. When the film is little seen on the surface, a crown-type splash is formed. The above difference of film separation is presumably caused by the increase in the film velocity according to the hydrophilic property of the solid wall and the attractive or repulsive force such as the electrostatic force between the solid wall and the water. This experimental observation suggests that the numerical simulation should take into consideration the various surface conditions or the interaction between the solid object and the water.

Let us discuss here how we can introduce the influence of the slippery wall seen, for example, in the case of the skin of a frog into the calculation in a heuristic manner. We take a diving sphere made of agar as the hydrophilic material, which consists of cross-linked structure by polymer called agarose and plenty of water molecule between the polymer structures, which makes the solid surface slippery. *Figure 3* shows schematically the velocity distributions of water flow near the surface of the acrylic-resin versus that of the agar-gel, where δ is the height of the water flow and u the velocity of the water. The slip ratio α is defined as follows,

$$\alpha = \tau' / \tau \qquad (1)$$



(A) Hydrogel (Agar) (B) Acrylic resin

Figure 2:
Comparison of splash patterns between hydrogel and acrylic resin (radius of sphere=10mm, impact velocity=2.21m/sec)

where τ is the wall shear stress under the no-slip condition and τ' that under the slippery condition. The wall shear stresses are obtained experimentally from the flow velocity near the wall as

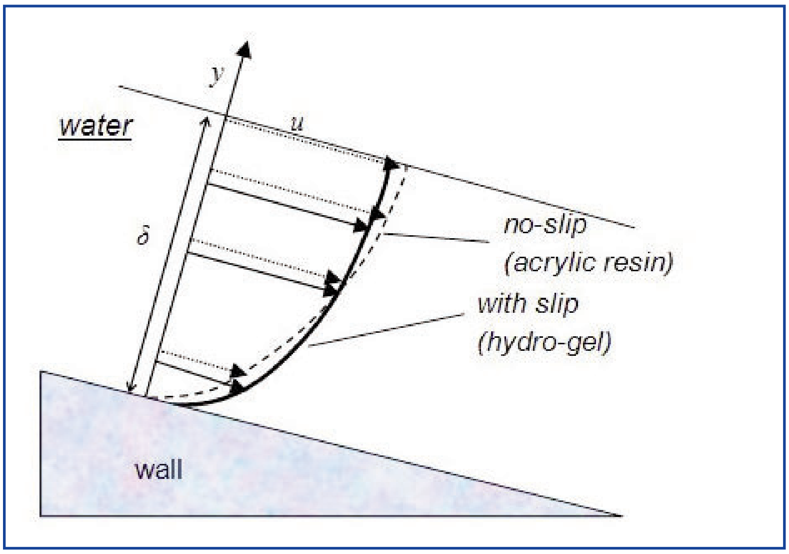
$$\tau = \mu \frac{du}{dy}\Big|_{y=0} \qquad (2)$$

where μ is the kinematic viscosity and u the flow velocity. *Figure 4* shows the experimental relations between the swelling ratio S and the slip ratio α for the agar-gel and the carrageenan-gel, respectively, where the swelling ratio S is defined as follows [15],

$$S = (m_{water} + m_{gel}) / m_{gel} \qquad (3)$$

where m_{water} is the mass of the water and m_{gel} that of the solid-gel. S increases with the amount of the water contained in the solid-gel.

Figure 3:
Schematic view of flow profiles near no-slip wall (acrylic resin) and slippery wall (hydrogel)



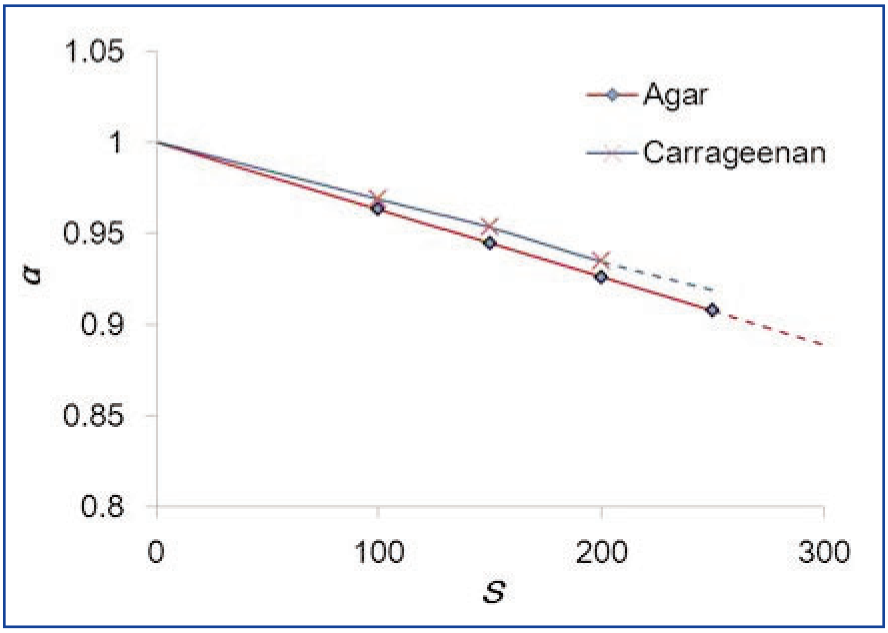
Agar employed in this study is a kind of hydrogel. *Figure 4* suggests that α can be expressed as

$$\alpha = 1 - \beta S \quad (4)$$

where β is a constant value estimated to be 1.2×10-3 in the case of the agar. It is summarized that larger S naturally gives more slip on the surface.

The above relation is taken into consideration in the vicinity of the solid wall in the viscous term of the Navier-Stokes equation in a heuristic manner.

Figure 4:
Experimental relationship between swelling degree S of hydrogels and slip ratio α



Since the shear force acting between the wall and the fluid is presumed to be directly related with the viscosity term of the Navier-Stokes equation, we modify the discretized form of the viscosity term [16] as follows,

$$\nabla^2 u = \frac{2d}{\lambda n^0} \sum_{i \neq j} \left[(u_j - u_i) \kappa_H (|\vec{r}_j - \vec{r}_i|) \right] \quad (5)$$

with

$$\kappa_H(r) = \alpha \kappa(r) \quad (6)$$

where i denotes the water particles near the hydro-gel wall and j the surface particles of the hydro-gel wall. Namely, α is set effective only near the hydrogel wall, because the effect of the slip is important only near this area.

The comparison of the MPS simulation result with S = 100 and the experimental one is shown in *Figure 5*, where the radius of the sphere R is 10 mm and the sphere is dropped from the height h =50R in the both simulation and experiment. The left hand side of *Figure 5* show the simulation result (top) and the snap-shot of the experiment (bottom) at t = 0.02 second after the sphere touches the surface of the water, respectively.

On the other hand, the figurers in the right hand side are those at t = 0.03 second.

References

[1] *Billah, K. Y., and Scanlan, R. H.*, **Resonance, Tacoma Narrows bridge failure, and undergraduate physics textbooks**, American Journal of Physics, (1991) 59, 118-124.

[2] *Pendergast, D. R., Mollendorf, J. C., Cuviello, R. and Termin, A. C.*, **Application of theoretical principles to swimsuit drag reduction**. Sports Engineering, (2006) 9, 65-76.

[3] *Moria, H., Chowdhury, H., Alam, F., Subic, A., Smits, A. J., Jassim, R. and Bajaba, N. S.*, **Contribution of swimsuits to swimmer's performance**. Procedia Engineering, (2010) 2, 2505-2510.

[4] *Fletcher, N. H.*, **Sound production by organ flue pipes.** The Journal of the Acoustical Society of America, (1976) 60, 926-936.

[5] *Coltman, J.W.*, **Sounding mechanism of the flute and organ pipe**. The Journal of the Acoustical Society of America, (1968) 44, 983-992.

[6] *Tsuchida, J., Fujisawa, T. and Yagawa, G.*, **Direct numerical simulation of aerodynamic sounds by a compressible CFD scheme with node-by-node finite elements**. Computer methods in applied mechanics and engineering, (2006) 195, 1896-1910.

[7] *Davies, J. M.*, **The aerodynamics of golf balls**. Journal of Applied Physics, (1949) 20, 821-828.

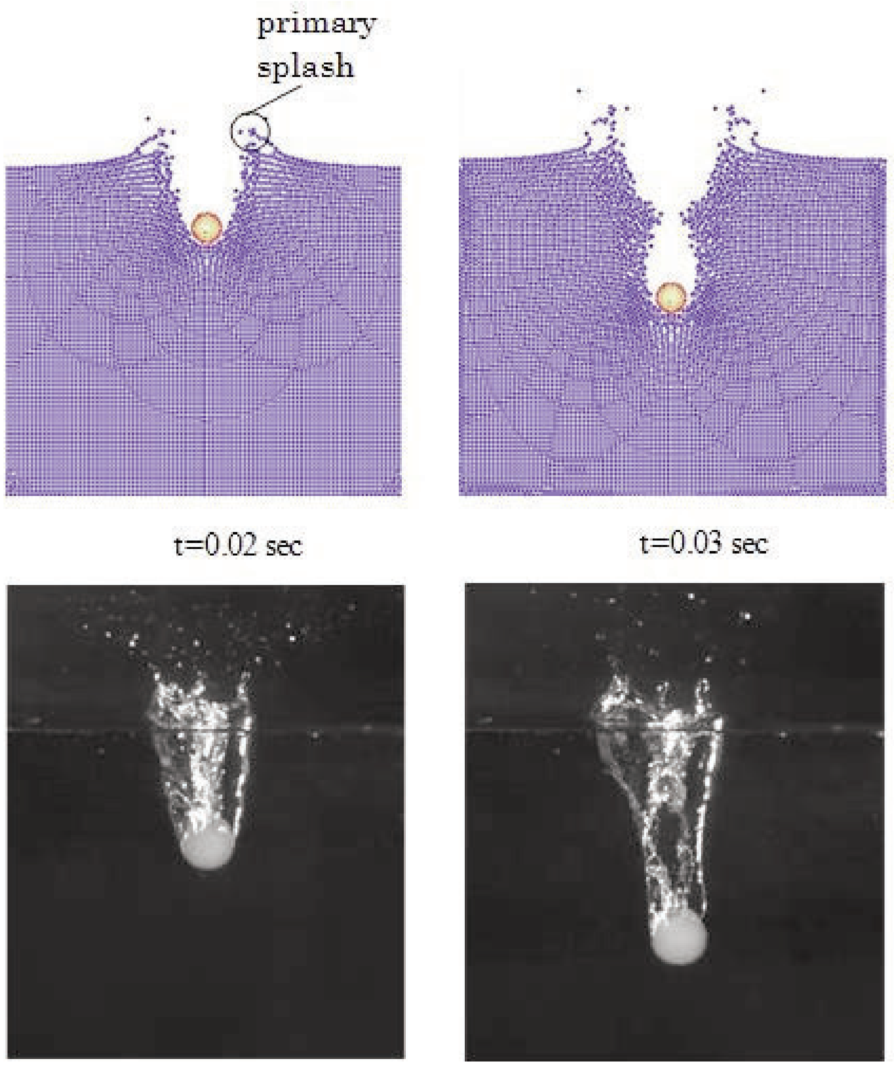


Figure 5:
Crown-type-splash of hydrogel (S = 100) by experiment and simulation, showing primary splash (t=0.02 sec) and air cavity (t=0.03 sec), respectively

The first splash, which is observed just after the hydro-gel sphere is dropped into water is called the primary splash. It is noted that the patterns of the crown-type splash and the air cavity by the present simulation are very similar to the experimental ones and that the above crown-type form and the occurrence of the air cavity are not seen in the case of the acrylic resin sphere. ●

[8] *Kodama, Y., Kakugawa, A., Takahashi, T. and Kawashima, H.*, **Experimental study on microbubbles and their applicability to ships for skin friction reduction**. International Journal of Heat and Fluid Flow, (2000) 21, 582-588.

[9] *Étienne, S. and Pelletier, D.*, **A general approach to sensitivity analysis of fluid–structure interactions.** Journal of Fluids and Structures, (2005) 21, 169-186.

[10] *He, T., Zhou, D., and Bao, Y.,* **Combined interface boundary condition method for fluid–rigid body interaction.** Computer Methods in Applied Mechanics and Engineering, (2012) 223, 81-102.

[11] *Maruyama, T.*, **Surface and inlet boundary conditions for the simulation of turbulent boundary layer over complex rough surfaces**. Journal of Wind Engineering and Industrial Aerodynamics, (1999) 81, 311-322.

[12] Ling, S. C. and Ling, T. Y. J., **Anomalous drag-reducing phenomenon at a water/fish-mucus or polymer interface**. Journal of Fluid Mechanics, (1974) 65, 499-512.

[13] *Worthington, A. M.*, **On impact with a liquid surface**. Proceedings of the Royal Society of London, (1882) 34, 217-230.

[14] *Kubota, Y. and Mochizuki, O.*, **Splash Formation by a Spherical Object Plunging into Water**. Journal of Visualization, (2009) 12, 339-345.

[15] *Alupei, I. C., Popa, M., Hamcerencu, M. and Abadie, M. J. M.*, **Superabsorbant hydrogels based on xanthan and poly (vinyl alcohol): 1. The study of the swelling properties**. European Polymer Journal, (2002) 38, 2313-2320.

[16] *Koshizuka, S.*, **A particle method for incompressible viscous flow with fluid fragmentation**. J. Comput. Fluid Dynamics, (1995) 4, 29-46.