Ultrasonic investigation of flow transition in surface switching of rotating fluid

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We have investigated the effect of surface tension in the recently reported phenomenon called "surface switching"; it occurs in the flow driven by a rotating disk in an open cylindrical vessel [1]. The deformed free surface abruptly changes from an axisymmetric to a non-axisymmetric shape accompanying with a change of typical height at irregular intervals. Ultrasonic velocity profiling (UVP) was utilized to measure the spatio-temporal fluid motion in three kinds of liquid; water, 10 cSt silicone oil and liquid gallium. The measurement and observation of the free surface indicate: (a) The silicone oil allows the breaking of axisymmetric flow and surface deformation even in the laminar region, but distinct surface switching is not observed. (b) The liquid gallium sustains the flow axisymmetry even in the turbulent region and the surface elongation does not occur. These results suggest that the surface tension as well as the viscosity play an important role in the mechanism of the surface switching.

Keywords: Rotating flow, Free surface, Flow transition, Instability, Surface tension, Liquid metal

1 INTRODUCTION

1.1 Background & Objective

Rotating flow accompanying with large-deformed free surface such as bathtub vortex is ubiquitous. The recently reported phenomenon called "surface switching" that occurs in the flow driven by a rotating disk in an open cylindrical vessel is one of the most interesting phenomena among them. Suzuki *et al.* [1] reported a temporally-irregular switching phenomena: the free surface shape changes the symmetry irregularly in time from axisymmetric to non-axisymmetric and vice versa while the height of the surface at the center of the vessel changes in the vertical direction. This "surface switching" is observed at $Re \sim 1.3\times10^5$, which is near the critical Reynolds number for the laminar-turbulent transition of the boundary layer on a rotating disk, $Re \sim 10^5$ [2]. They suggested that the mechanism of the switching is the decrease /increase of the pressure in the central region caused by the laminar-turbulent transition of the flow. Tasaka *et al.* [3] studied the transition to surface switching using flow visualization. As mentioned above, the critical Re for the switching is close to the turbulent transition of the boundary layer on a rotating disk [2]. Therefore the turbulent transition may be a trigger for the large scale deformation of the surface. However, there are other possibilities that the centrifugal instability and/or the inertial instability induce the large-scale deformation. Tasaka & Iima [4] studied the flow transition in the region below the critical Reynolds number of surface switching to investigate the qualitative fact about the flow characteristics that may lead to the surface switching. They find that the fluid-air interface becomes unstable at a smaller Reynolds number than the critical Reynolds number for the surface switching.

This phenomenon has at least four control parameters; Reynolds number, Froude number, Weber number and aspect ratio. This study aims to clarify the effects of the Weber number using various liquids; water, 10 cSt silicone oil and liquid gallium.

1.2 Process of the temporally irregular switching

Figure 1 shows a typical sequence of the switching. (a) The bottom of an axisymmetric surface elongates and attaches to the rotating disk. (b) The shape of the surface changes into non-axisymmetric shape. (c) Deformation of the surface becomes large and finally the surface detaches from the bottom. (d) The surface with two humps rotates. (e) The free surface restores axisymmetry and then elongates to the bottom.

The detailed dynamic process consists of the

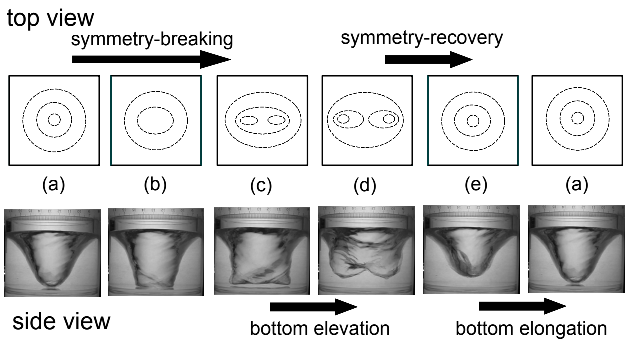

Figure 1: Visualization of the shape of the free surface during the switching process; top view (above, schematic) and side view (bottom, visualization). The free surface repeats its deformation from (a) to (e)

following three states; surface switching (SW), regular oscillation (RO) and flat rotation (FR) [4]. Figure 2 shows a temporally expanded image extracted from snapshots of a movie taken from a side by constructing their middle lines. Rectangles indicate each state; (a) SW, (b) RO and (C) FR. SW shows the large depression of the surface due to the flow transition from turbulent to laminar. RO sustains a periodic oscillation of the surface with keeping the non-axisymmetric shape with clear humps (see figure 1 (d)). In FR the bottom of the surface looks flat and it has no clear humps.

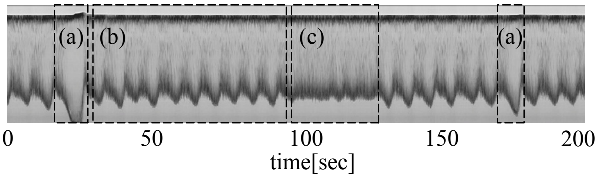

Figure 2: Typical variation of the surface height in the temporally irregular surface switching extracted from a movie at the vertical center line of the cylinder, where labels (a), (b) and (c) represent surface switching (SW), regular oscillation (RO) and flat rotation (FR) respectively.

2 EXPERIMENTAL SETUP AND METHOD

Figure 1 (a) shows a coordinate system and a schematic diagram of the experimental setup. The open end cylindrical vessel is made of acrylic resin for water and silicone oil or tin for liquid gallium; its inner radius is $R = 42$ mm. A disk is also made of two kinds of material; glass for water and oil, and tin for gallium because of wetting properties. The disk was driven by a stepping motor through a shaft. A gap between the disk and the side wall of the vessel, $\Delta R = 0.3$ mm, was set to reduce a vibration due to the friction. The height of the liquids at rest was $H = 40$ mm; and the aspect ratio $\Gamma = H/R = 0.95$. Particles of porous resin or ZrB2, which are 50 to 60 μm in diameter, were mixed into the fluids as tracers for the velocity profile measurement. The liquid gallium layer was surrounded by Argon gas to prevent oxidization. The physical properties of the working fluids are specified in table 1. Reynolds number in this system is defined as $Re = 2\pi\Omega R^2/\nu$ (here Ω and ν are the rotating speed [rad/s] of the disk and kinematic viscosity of the fluid respectively).

Ultrasonic velocity profiling (UVP) was used to determine instantaneous velocity profiles. It is capable of measuring the spatio-temporal motion of fluid even in opaque fluid such as liquid metal [5, 6]. An ultrasonic transducer was mounted at the side wall of the vessel perpendicular to the wall at a height of 8 mm from the disk ($z/H = 0.2$). Instantaneous profiles of the radial velocity component along the horizontal center line of the cylinder, $u(r, t)$, were measured through the side wall. The contact face of the vessel with the transducer was flattened to improve transmission of the ultrasonic wave through the cylinder wall. The basic frequency of the ultrasonic wave was set to 4 MHz; the spatial resolution of the velocity profile, which is determined from the wavelength of the ultrasound, is 0.74 mm for water, 0.5 mm for silicone oil and 1.43 mm for liquid gallium. The number of the velocity profile is 4096.

The free surface of the water was illuminated by a back light (Halogen lamp scattered by tracing paper) from a side of the cylinder, and its motion was captured by a digital video camera.

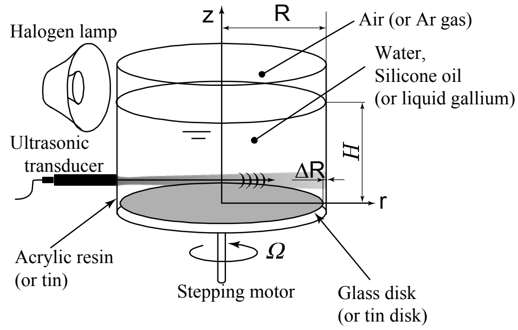

Figure 3: Experimental setup for the UVP measurement and the surface height measurement; Materials of the vessel are acrylic region and glass for water and silicone oil or tin for liquid gallium.

Table 1: Comparison of physical properties (kinematic viscosity ν, surface tension σ and speed of sound c) in working fluids, water, 10 cSt silicone oil and liquid gallium

Liquid	ν [m^2/s]	σ [N/s]	c [m/s]
Water	1.0×10^{-6}	0.073	1480
Silicone oil	10.0×10^{-6}	0.021	995
Gallium	0.32×10^{-6}	0.715	2860

3 RESULTS AND DISCUSSIONS

3.1 Silicone oil (low surface tension & high kinematic viscosity)

In the silicone oil, the rotating fluid loses axisymmetry even at small rotating speed because of small surface tension (see Table 1). Such symmetry-breaking is reported by *Lopez et al.* [7], but it is not distinct in the case of water. Figure 4 shows mean velocity profiles on the horizontal line through the center of the cylinder; (a) the silicone oil and (b) water. Error bars in the figures represent the standard deviation of the velocity fluctuation. The rotating speed is 300 rpm in the both cases and corresponding Reynolds numbers are 0.55×10^4 for the oil and 0.55×10^5 for the water. In water a local circulation forms a central region of the cylinder but the radial velocity is small in other area when rotating speed is small [3]. Figure 4 (b) follows this: There are large mean velocity and large velocity fluctuation around the center. In the silicone oil, mean velocity is small but the fluctuation is quite large (up to around 60 mm/s) from the center to $r/R \sim 0.75$. Mean velocity neat the wall has a relatively large value. It is caused by a local circulation near the wall. Figure 5 shows typical surface shape for the silicone oil, where the schematics attached on the pictures indicate the shooting angle for the surface. The free surface has certain non-axisymmetric shape but it has never taken the humps which are observed in the water (cf. Fig.1 (d)). In this sense, this state looks as flat rotation (FR) observed for the case of water (cf. Fig. 2 (c)). Rotation of this surface causes the oscillation in the fluid flow. The surface also has a stair-like shape near the side wall corresponding to the boundary of the local-circulation region near the wall. Such the shape has never observed in water.

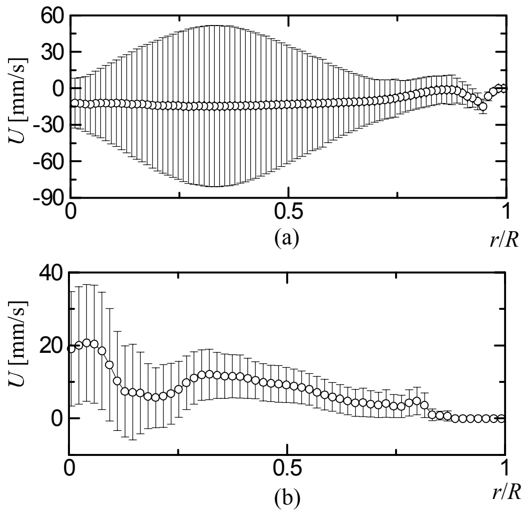

Figure 4: Mean velocity profile on the center line of the cylinder; (a) 10 cSt Silicone oil and (b) water, where the error bards represent the standard deviation of the velocity fluctuation (rotating speed is 300 rpm in the both cases.)

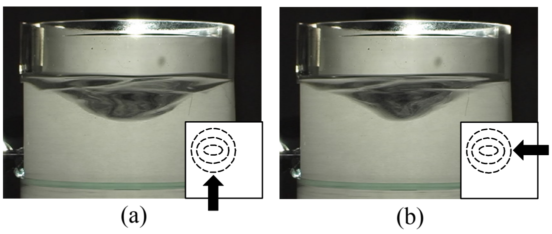

Figure 5: Typical pictures of the surface shape in 10 cSt silicone oil, where the schematics attached on the pictures indicate angle for the non-axisymmetric surface (300 rpm)

Figure 6 shows the spatially averaged intensity of the velocity fluctuation for the silicone oil and water [4] as the function of (a) rotating speed (proportional to the Froude number, defined as $Fr = 2\pi\Omega R/(gH)^{1/2}$) or (b) the Weber number ($We = \rho U^2 R/\sigma$, where g, U, ρ and σ are gravity acceleration, characteristic velocity, density and surface tension of the fluids. We choose here the rotating velocity at the edge of the disk, $2\pi\Omega R$, as U for simplicity). In the water the intensity decreases with respect to the rotating speed until the surface attaches to the bottom (around 500 rpm). It greatly increases at the onset of the switching (around 760 rpm). In the silicone oil, the intensity rises sharply at a small rotating speed, around 200 rpm, by the surface deformation (cf. Fig. 5). It sustains a constant value until 350 rpm, and after that, it is roughly proportional to the rotating speed. In this region, the height of the free surface gradually decreases as the rotating speed increases. But it should be noted that the rate is smaller than the water because it is prevented by an increment of the pressure at the central region of the cylinder due to the flow mixing by non-axisymmetric surface. The visualization of the surface shows that it attaches to the bottom around 650 rpm, which is substantially larger than the case of water; however, there is no data larger than 600 rpm because of the measurable velocity range of UVP. It also shows that the surface never detached from the bottom even at 850 rpm. The surface is also deformable in this condition. But it cannot produce large velocity fluctuation enough to detach from the bottom against the pressure gradient; because the Reynolds number is much smaller than water due to the large kinematic viscosity.

Figure 6 (b) shows the Weber-number dependency of the spatially averaged velocity fluctuation intensity. Appearance of the surface deformation is in the same order of We in the both cases. But the flow phenomenon is quite different as explained follows.

Figure 7 (a) shows the apace averaged power spectrum of the velocity fluctuation in the silicone oil; the averaging area is $0.49 \le r/R \le 0.67$. There are

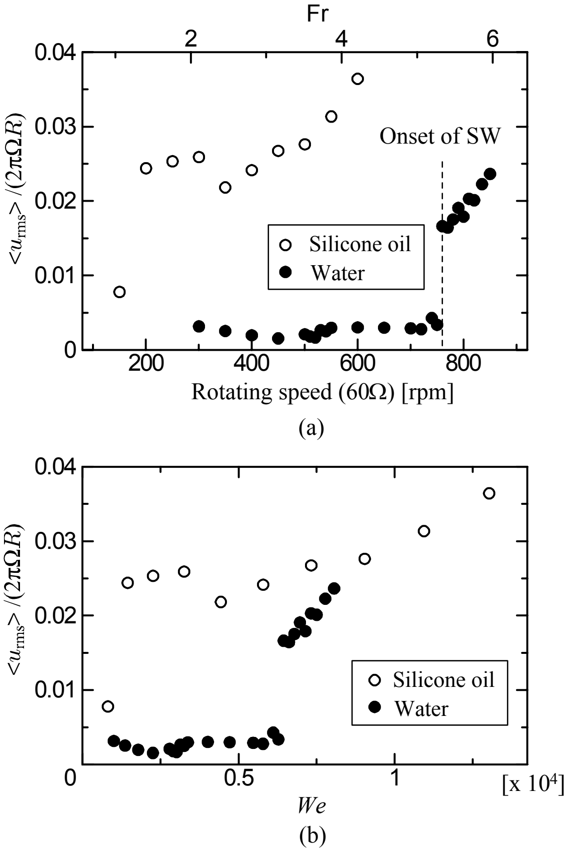

Figure 6: Spatially averaged intensity of the velocity fluctuation for 10 cSt silicone oil and water versus (a) rotating speed and Froude number or (b) Weber number

clear peaks of f_1 and its harmonics. f_1 corresponds to the rotation of the non-axisymmetric surface. In comparison with the spectrum for the temporally irregular switching in water (Fig. 7 (b), 850 rpm), there are no other frequency components than f_1, f_2 or f_3 in the Fig. 7 (b), which corresponding to the vertical oscillation of the surface or irregular switching. We observe such a regular oscillation appears in the silicone oil around 500 rpm, where the surface is close to the bottom, but its amplitude is substantially small than the surface switching.

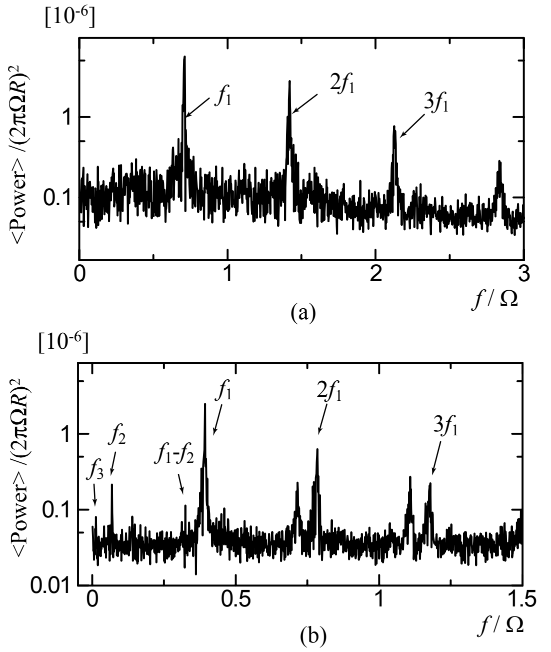

Figure 7: Space averaged power spectra of the velocity fluctuation; (a) in 10 cSt silicone oil with 300 rpm in the rotating speed and (b) in water with 850 rpm

3.2 Liquid gallium (high surface tension & low kinematic viscosity)

Figure 8 shows the mean velocity profile in the liquid gallium; (a) on a line, ξ, parallel to the line through the center of the cylinder, with a distance Δy and (b) the line through the center. A schematic in Fig. 8 indicates the relation between the measurement lines. Figure 8 (b) shows that value of the radial velocity is very small along the line through the center of the cylinder except several negative values around $r/R = 0.5$; it may be due to the measurement error. It means that the fluid motion is fully axisymmetric. The velocity profile on the measurement line ξ provides that the velocity has an azimuthal component as shown in Figure 8 (a). Comparing with Fig. 4 (b), we observe that in the water case the local circulation at the central part of the cylinder causes the velocity fluctuation. Such a large fluctuation is not observed in the gallium case, because the surface tension is so large (around ten times larger than water) that the symmetry-breaking of the surface deformation is depressed. The height of the free surface gradually decreases with respect to the rotating speed. It should be noted that the rate is smaller than the water because the large surface tension prevents the elongation of the free surface. It does not attach to the bottom even at 700 rpm.

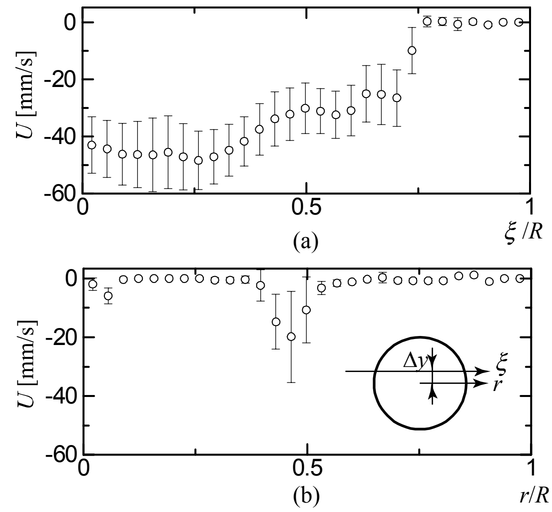

Figure 8: Mean velocity profile of the rotating liquid gallium (a) on a line parallel to the center line with a distance and (b) on the center line

4 CONCLUSIONS

I was shown that the surface tension greatly influences the temporally irregular surface switching using three kinds of liquids. 10 cSt silicone oil allows the surface deformation even at a small rotation speed. But the surface switching is not observed even at the critical rotating speed of the switching in the water because of large kinematic viscosity. Large surface tension of the liquid gallium sustains the flow axisymmetry and prevents the surface elongation.

ACKNOWLEDGEMENT

This work is supported by Grant-Aided Research for Science of the Japanese Ministry of Education & Science: No.18760116 and No.18204038. The authors express thanks for this support.

REFERENCES

[1] SUZUKI T, *et al.*: Surface switching of rotating fluid in a cylinder, Phys. Fluids 18 (2006) 101701.

[2] REED HL, SARIC WS: Stability of three-dimensional boundary layers, Ann. Rev. Fluid Mech. 21 (1989)235-284.

[3] TASAKA Y, et al.: Visualization of a Rotating Flow under large-deformed Free Surface using anisotropic Flakes, J. Visualization 11(2008) 163-172.

[4] TASAKA Y, IIMA M: Flow transition in surface switching of rotating fluid, in progress.

[5] TAKEDA Y: Measurement of velocity profile of mercury flow by ultrasound Doppler shift method, Nuclear Tech. 79 (1987) 120-124.

[6] MASHIKO T, *et al.*: Instantaneous measurement of velocity fields in developed thermal turbulence in mercury, Phys. Rev. E 69 (2004) 036306.

[7] Lopez JM, *et al.*: Symmetry breaking in free-surface cylinder flows, J. Fluid Mech. 502 (2004) 99-126.