# Collision of a Vortex Ring on Granular Layer

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An experiment on the collision of a vortex ring on a granular layer was performed. The vortex ring deformed at the impingement on the surface of the latter, and a rosette-like wrinkle was observed under certain Reynolds numbers of the vortex ring and bed height. The engraving process, the Reynolds number dependence on the patterns, and the relation to the depth of the granular layer were examined.

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In this paper we report our experimental results on the behavior of a vortex ring, which impinges perpendicularly to an initially flat (in the macroscopic sense) granular boundary, as well as the patterns left on its surface. This mechanism can be applied to remove slurries of sea bed, or can be used to explain a possible formation of the Rampert crater on Mars.

**Experimental apparatus** We show our experimental setup in Fig.1. A vortex ring was generated in water by impulsively ejecting the same fluid vertically downward through a circular pipe of an inner diameter 24 mm. The acceleration and duration of the ejected water were controlled by the computer, which derived the piston-motor system. The test section had a dimension 500 × 500 × 700 $\mathrm{mm}^3$. The behavior of the vortex ring was visualized by sodium fluorescein, which were supplied at the edge of the pipe. By tracing the vortex ring, we firstly measured the translational velocity of the latter $U$ as well as the ring radius $R_0$ and the core radius $a$. The reproducibility of the vortex ring was satisfactory. Circulation of the vortex ring $\Gamma$ was estimated by using the Kelvin's formula. The typical Reynolds number $Re \equiv \Gamma/\nu$ ($\nu$ is the kinematic viscosity) ranged from 1600 to 5000. Secondly, we placed a granular layer of glass beads of a diameter $d$ = 0.10± 0.01 mm horizontally with constant thickness $h$ in the central part of the test section, and the deformation of the granular surface were observed by a digital video camera. The layer thickness $h$ was varied whereas the distance $H$ between the edge of the pipe and the granular surface was kept constant, and their dependence were examined.

**Trajectory of the vortex core** We show an example of the trajectory of the vortex core in Fig.2, which corresponds to the Reynolds number $Re$ =4700. We note that the behavior is almost the same for $Re$ lower than about 2000 except the collision with the fluid plane. In this $Re$ region the vortex ring has not large enough impulse to deform the granular surface, so that no difference was recognized between the rigid boundary and the granular surface. Apparently the vortex ring can approach closer to the liquid plane, because the latter exerts less stress than that toward a solid plane. On the other hand, the difference becomes pronounced for $Re$ larger than about 2000. In this case, the vortex ring induces sufficiently strong flow, which makes the grains on the surface in motion. The kinetic energy and momentum of the vortex ring is dissipated by engraving the surface, so that the penetration depth of the vortex ring into the granular layer is reduced. This reduction is larger for thicker granular layer. The above tendency is the same for a vortex ring of $Re$ =4700, but the trajectories after collision become more flat, which suggests that the vortex ring loses most of the energy and momentum and that the rebound or secondary vortex is not induced.

**Patterns on the granular layer** In our Reynolds number region, the vortex ring were associated with the Widnall instability when it traveled a certain distance in free space as shown schematically in Fig.3. The number of waves of a vortex ring, ranging 6 to 12, depends on the Reynolds number $Re$, the ratio $R_0/a$, and the traveling distance. The part of the ring with larger local curvature moves faster, so that it deviates from a plane. As a consequence, the wavy protruding parts of the vortex ring touch the granular plane first, and sweep its surface radially.

Figure 4 shows an example of collision of a vortex ring on the granular surface. The Reynolds number of the vortex ring $Re$ is 4700, and the layer height $h$ is 1.5 mm. In Fig.4(a) outer edge of the vortex ring (vortex blob) touches the granular layer, so that the depression of the layer is almost circular. The front part of the wavy core region reaches the granular layer in Fig.4(b), and sweeps the granular layer in the radial direction. The wavy core region of 180° out of phase reaches the granular layer in Fig.4(c), and sweeps the surface of the boundary similarly but the positions of the ditches are between the previous ones. The second collision, however, is not always accompanied. For $Re$ =2800 single star-like ditches corresponding to the first collision are observed, whereas it is doubled in $Re$ =4700 case reflecting two-step collisions. In the former, the vortex ring rebounds after the first collision, so that the vortex core lies outside of the interaction region. On the other hand, the vortex core remains close enough to the granular layer in the latter, and the second engraving occurs.

Our pattern formation depends not only on the magnitude of the vortex ring, but also on the properties of the granular material. By changing the layer depth $h$ while keeping the distance $H$ between the orifice of the nozzle to the plane, we found that the "penetration depth" of the vortex ring decreases with the layer number up to about 10, and attains a constant level. A model of vortex collision taking account of the effect of energy dissipation is proposed.

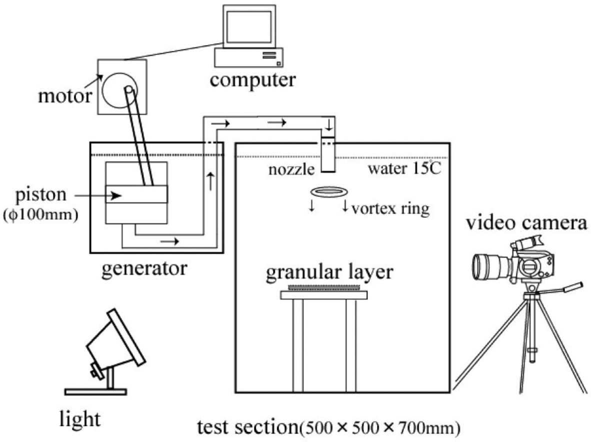


Fig.1. Schematic diagram of the experimental apparatus.

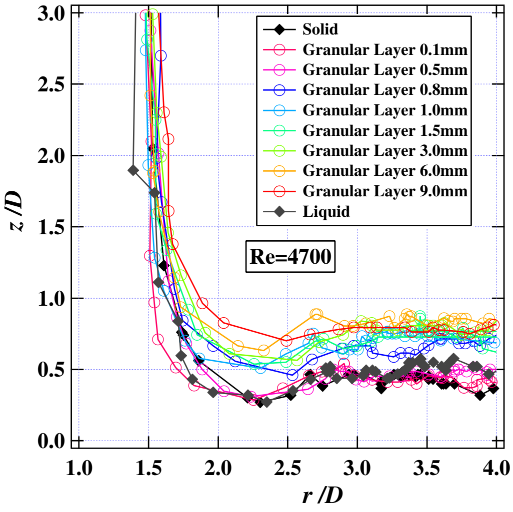


Fig.2. Trajectory of the vortex core: (a) $Re$=1800, (b) $Re$=2200, and (c) $Re$=4700. Different boundary conditions are compared.

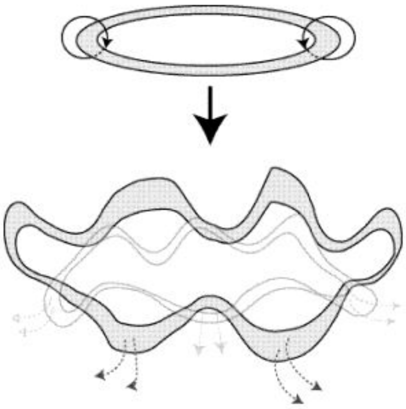
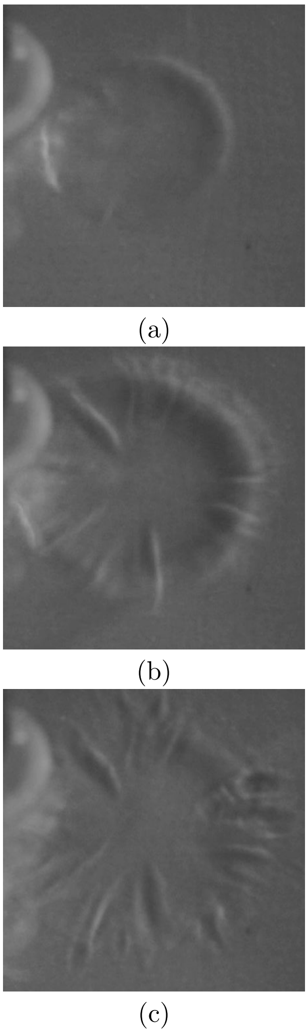


Fig.3. Schematic picture of the Widnall instability and the associated motion of a vortex ring.



(a)

(b)

(c)

Fig.4. Time sequence of the collision of a vortex ring ($Re$ =4700) on the granular layer: (a) vortex blob reaches the granular surface ($t$ =0.48 s), (b) front part of the wavy vortex core touches the boundary and engraves it in the radial direction ($t$ =0.51 s), (c) the vortex core, previously in

the rear side, rolls down to scratch the boundary ($t$ =0.81 s).