# Impact of a circular disk with flat, concave and convex bottom on shallow water

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**Introduction.** Impact of a solid body on water surface has been a subject of extensive research owing to its practical importance in applications such as slammimg, gliding, hydroplane landing, etc. A considerable body of theoretical results has been obtained within the realm of ideal-fluid model, with effects of air neglected, both in deep water (classic Wagner problem and its modifications) and in shallow water [1 – 4]. However, for flat-nosed bodies the dynamics of entry into the water (in particular, magnitudes and time-scales of pressure and acceleration) is interrelated with the behavior of the air cushion trapped under the bottom of the body (see [5 – 7] for deep- and [8] for shallow-water cases). Recent theoretical studies on air cushioning with air-water lubrication-inviscid balance in deep- [9] and shallow-water [10] cases reveal the possibility of air-trapping at the nose of convex bodies. Thus, the interest to the effects of air cushioning is extended from flat-nosed bodies (zero bottom curvature) to the bodies with a non-zero curvature of the bottom.

In this report we present an experimental study of the effects of small positive and negative curvature of the bottom of a circular disk on the flow patterns and dynamic properties of impact on shallow water. In particular, we focus on the possibility of air trapping by a convex body and the effect of air trapping on touchdown of the body onto the bottom of the test tank in a shallow-water setup. The dynamics of the bottom touchdown in the cases of convex, flat and concave bodies is compared. The data of visualization with a high-speed camera are complimented with the measurements of acceleration of the disk and the pressure acting on the bottom of the test tank at different stages of impact.

**Experimental setup.** Experiments were carried out at LIH in a test tank of size $120 \times 120 \times 30$ $\text{cm}^3$. The scheme of experimental installation is shown in figure 1. The tank was filled with distilled water to the depth $h$, which varied from 1 to 6 cm. The walls and the bottom of the test tank were made of acryl glass. Both side view and bottom view were used for visualization. The major part of information on the physics of the phenomena was inferred from the bottom view. For visualization we used high-speed camera MotionXtra HG-100K (Redlake) operated at the frame rate from 500 to 2000 frames per second.

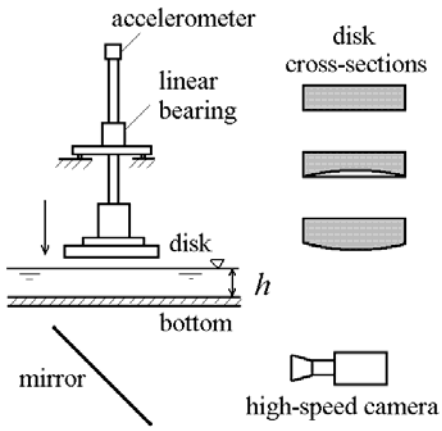
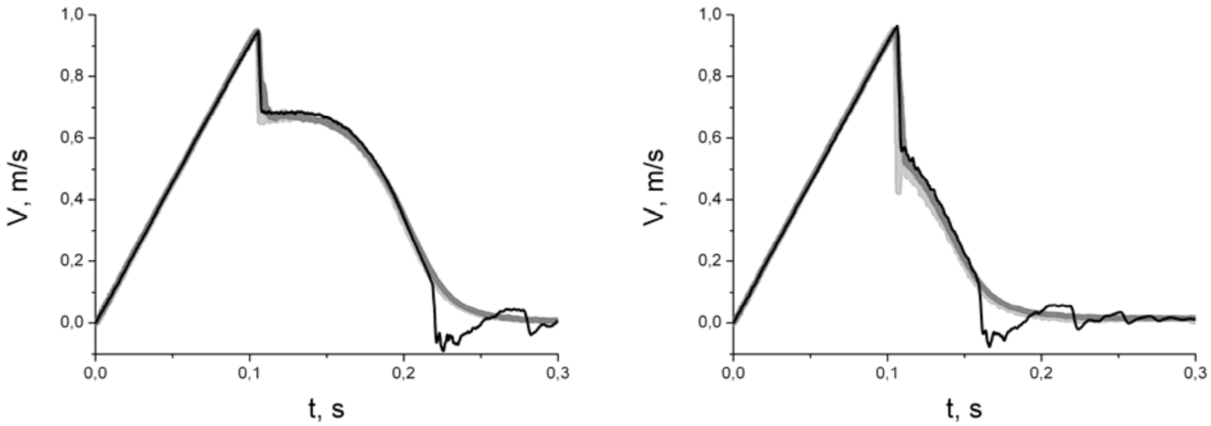



Figure 1. Experimental setup

Drop tests were conducted with a set of acryl disks of diameter $d = 18$ cm and thickness 3cm. The bottom side of the disks was either flat, or carefully machined to have a prescribed radius of curvature. In experiments we have used convex disks with the radius of the bottom curvature $R = 1$ and 1.3m, and a concave disk with $R = 1.3$ m. The lower surface of the disks was painted white. Pressure at the bottom of the test tank was measured by a KYOWA probe having natural frequency 32kHz. The drop height $H_{drop}$ measured from the lower surface of the disks to free surface was constant in all experiments ($H_{drop} = 5$cm). A vertical steel rod was attached to the disks. The rod could slide free in a linear bearing serving as a guide. An accelerometer with operational frequency up to 1kHz was attached to the upper end of the rod. The mass $M$ of the disk with the rod was 2.72kg in all experiments

**Results and discussion.** Typical time-histories of the velocity of the disk are shown in Fig. 2. Velocity $V$ is obtained by integrating acceleration. One can see the straight line corresponding to the free fall, with the terminal velocity just before the impact $V_{-0} = 0.95$m/s (about 4% smaller than the theoretical value for the impact height 5cm). After the collision with free surface the velocity drops to the value $V_{+0}$, which weakly changes with the bottom curvature. It means that a small bottom curvature in a shallow water setup only weakly affect the momentum imparted by the disk to the fluid. The velocity drop due to impact agrees well with the predictions of [11] and preliminary experimental estimates presented in [8] for a flat-bottom case. However, the bottom curvature has a strong impact on the time-scale of the impact phenomena. The shortest timescale is typical for the flat disk, yielding the largest values of the impact acceleration. The time-scale is the largest for a disk with the concave bottom, yielding accelerations 2-3 times smaller than in the case of a disk with a flat bottom. The convex-bottom case is intermediate between the flat- and concave-bottom cases. As it could be expected, the impact acceleration increases as water depth $h$ decreases. One can see that after impact the velocity decreases with time in a way, which is qualitatively and quantitatively similar for all disks up to a certain critical time when the convex disk makes a touchdown to the bottom (see thin black lines in Figs. 2 *a)* and *b)*. After hitting the bottom, the convex disk jumps so that its velocity becomes negative, falls down to the bottom again, etc. Typically, it makes 3 clearly detectable jumps. In contrast to the convex-bottom disk, both flat- and concave-bottom disks approach the terminal zero velocity smoothly, in a monotonous way.




*a)* *b)*

Figure 2. Velocity of the disk versus time: a) $h = 6$ cm and b) $h = 2$ cm; light gray, grey and black lines correspond to disk with flat, concave and convex bottom, respectively. In all cases drop height is $H = 5$ cm, radius of the bottom curvature of concave and convex disks was $R = 1.3$m.

The high-speed visualization of the flow is shown in Fig. 3. The frame rate in this series of experiments was 1000 frames per second. So, initial time $t_{ini}$ could not be determined with accuracy better than 1ms. The first image approximately corresponds to time 1ms after the first contact of disk with water. One can clearly see a circular trapped air region in the center of the convex disk (left column in Fig.3). Grey zone is the zone of contact with water. Further, the cavity collapses into a central bubble. Just before the touchdown the position of the central bubble becomes unstable. It is washed away from the centre where it ‘explodes’ (see the largest light-grey region at the lowest left image, to the left from the center of the disk). The edge of the initial air cavity is seeded with microbubbles serving as nucleus for cavitation which happens when the convex disk hits the bottom of the test tank. These microbubles also ‘explode’.

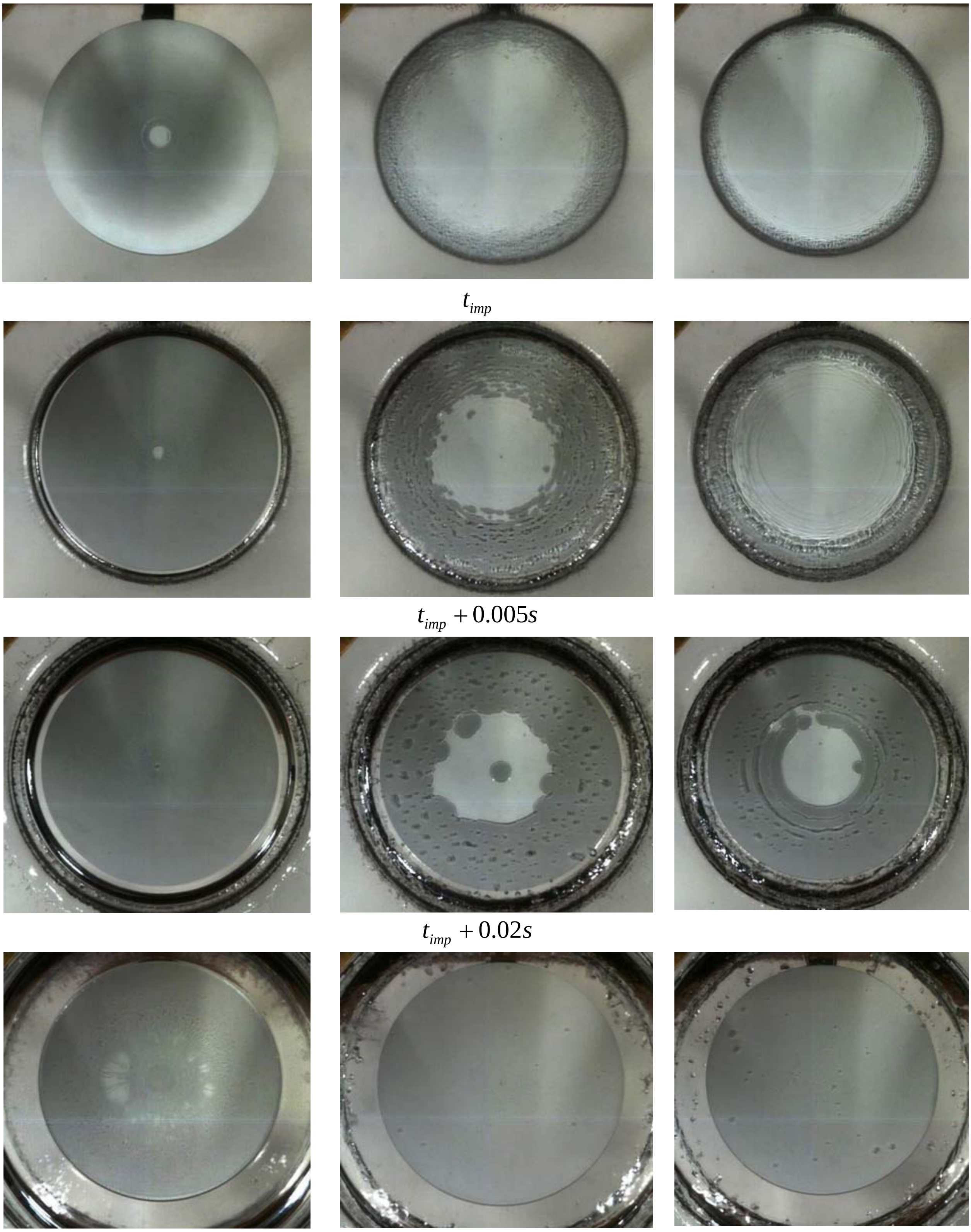



Figure 3. Flow patterns observed through the bottom of the test tank at different stages of impact for circular disks with convex (*left*), flat (*center*) and concave (*right*) bottoms. The upper row corresponds to the moment of impact $t_{imp}$, the regions of air trapping can be easily identified. The lower row corresponds to time $t_{imp} + 0.11s$ when the convex-bottom disk makes a touchdown to the bottom of the test tank. Cavitation regions in the left lower image can be identified. The central bubble is washed to the left where it ‘explodes”. In all cases drop height is $H = 5$ cm, radius of the bottom curvature of concave and convex disks was $R = 1.3$ m.

Since the continuity breaks up, the convex disk hits the bottom at certain non-zero speed (producing a clear sound of impact to the test-tank bottom) Further, it jumps after the touchdown. It is noteworthy, that if the assumption of continuity holds true, theoretical analysis predicts a smooth asymptotic approach of velocity to zero value when a concave body approaches a rigid wall [12]. In experiments we observe such a smooth monotonous approach only in the flat- and concave-bottom cases (see Fig. 2). In the cases of flat and concave bottom (see central and right columns in Fig. 3), the trapped air region initially extends over the whole lower surface of the disk. The edge of the air cavity is unstable. It is destroyed forming ring-shaped structures. The largest ring-shaped structure forms at distance $0.4d$ from the centre both in flat- and concave-bottom cases. Eventually, the air cavity breaks up into bubbles which are carried by the flow of water away from the gap between the disk and the tank bottom.

**Conclusions.** This report presents an experimental study of shallow-water impact problem for circular disks having flat, convex and concave bottoms. It is shown that small curvature of the bottom weakly affects the overall velocity drop during the collision of the disks with the free surface. However, small curvature strongly affects the time-scales of impact onto free surface. The shortest and longest impact time-scales are observed for flat- and concave-bottom cases, respectively. The convex-bottom case is the intermediate one. The largest accelerations have been observed for the flat-bottom case. Introducing small bottom curvature one can decrease impact acceleration (for concave-bottom disk maximum impact acceleration is 2-3 times smaller than in the case of flat-bottom disk). The dynamics of approach of a disk to the bottom of the test tank strongly depends on the curvature of the bottom of the disk. It is shown that air-trapping occurs in all the cases studied. In the convex-bottom case air is trapped in a small region around the center of the disk. This region collapses into a bubble which persists at the center of the disk up to the contact with the bottom. At the edge of initial air-trapping region the surface of the convex disk is seeded with microbubbles serving as nucleus for cavitation when the disk makes a touchdown to the bottom. The details of visualization and the results of pressure and acceleration measurements at different depths of fluid will be presented at the workshop.

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