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OBLIQUE COLLISIONS OF NON-ROTATING SPHERICAL PARTICLES WITH A WALL

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Abstract: *In the present paper non-rotating particle-wall collisions were experimentally investigated. By means of the PIV method a velocity field around falling spheres was analyzed. It was shown that the wake behind the particle which approached a bed in non-normal direction was asymmetrical and after the impact the wake passed the particle only along one side. This non-symmetrical velocity field resulted in additional forces which pushed the particle to an opposite direction than was the direction of the particle motion just after the impact.*

Keywords: ***Wake, particle trajectory, velocity field***

1. Introduction

A large number of experimental and numerical studies of the wake behind the sphere has been performed. Thompson et al. (2007) have investigated the flow dynamics associated with the normal impact of a sphere with a wall both numerically and experimentally for Reynolds numbers 100<Re<2000. The experiments were carried out in a glass tank. A brass sphere 19.02 mm in diameter was attached to a fine thermally fused twisted stretch-resistant thread. Care was taken to ensure that the attachment was as clean as possible to avoid the introduction of extraneous disturbances to the flow during the experiments. The thread passed over a pulley and was wound on a threaded reel driven by a high-resolution computer-controlled stepper motor. This mechanism allowed the sphere to be lowered through the water at a specified uniform speed thereby allowing selection of the Reynolds number. During the experiments, there were no noticeable oscillations of either the sphere or supporting thread. Theirs experiments indicated that the collision remains essentially axisymmetric for Re < 1000. Eames & Dalziel (2000) experimentally investigated the hydrodynamic mechanism of dust resuspension as function of Reynolds number for 300<Re<3500. The study has shown that when a sphere collides with a wall, the wake vortex which is initially behind the body, threads over the sphere's surface generating a secondary vortex. The coherent structure, composed of the wake vortex and secondary vortex, collides with the wall, pushing fluid which is adjacent to the wall to one side, which is subsequently entrained by the wake vortex.

In our study we have focused on a rebounding of spherical particles from the bed when the particles approached the bed in non-normal direction.

2. Experimental arrangements

The experiments were realized in a water tank of dimensions 400 x 200 x 280 mm. The tank was filled with water up to a level 230 mm above the bed. The bed was formed by a glass plate of thickness 19 mm. We used two types of spherical particles:

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- plastic sphere of diameter 37.5 mm and density 1028 kg/m^3

- golf ball of diameter 42.8 mm and density 1120 kg/m^3.

The particle movements in water were recorded using a digital video camera NanoSence III+ with a frequency of 700 frames per second (plastic particle) and a frequency of 1000 frames per second for the golf ball. The flow field was visualized by aluminium seeding particles and a light sheet entered the water tank from the left side. To perform a PIV analysis we used the Time-resolved digital particle image velocimetry tool developed for Matlab. To capture the particle trajectories we used functions implemented in the Matlab Image Processing Toolbox. Details of image capturing and analyzing were published in (Chara et al., 2012). The important parameter controlling the impact process is the non-dimensional distance L/D, where L is the initial distance between the bottom of the sphere and the wall a D is the particle diameter. In our experiments the ratio was L/D = 4 - 5. The spheres were held between cups below water level and when the trigger was released, the springs pulled the cups apart, allowing the ball to fall freely in water. The Reynolds numbers varied from 5000 to 13000.

3. Discussion of the results

Fig. 1 shows trajectories of the plastic particle which freely falls for different experimental runs. Since the ratios of densities of both types of particles to water density were close to one, the particles had tendency to fall not along a straight line but rather along a curved line (Horowitz & Williamson, 2010). The particle strikes the wall at an oblique angle and after the impact the particle seems to follow a path resulting from the law of reflection. But after a short time after the impact the particle is suddenly moved to an opposite direction. Such behavior was also observed for the golf ball, see Fig. 2. To explain this behavior we analyze the wake formation during the falling and the rebounding period. In Fig. 3 there are shown the velocity vectors in a plane going through the centre of the plastic particle. The velocities are relative to the instantaneous particle fall velocity. The dimensions in Fig. 3 are in millimetres. As can be seen in Fig. 3 the wake behind the particle is shifted to the left during the falling period. When the particle touches the wall the wake moves towards the wall mainly along the left side of the particle and the velocity field around the particle is asymmetrical.

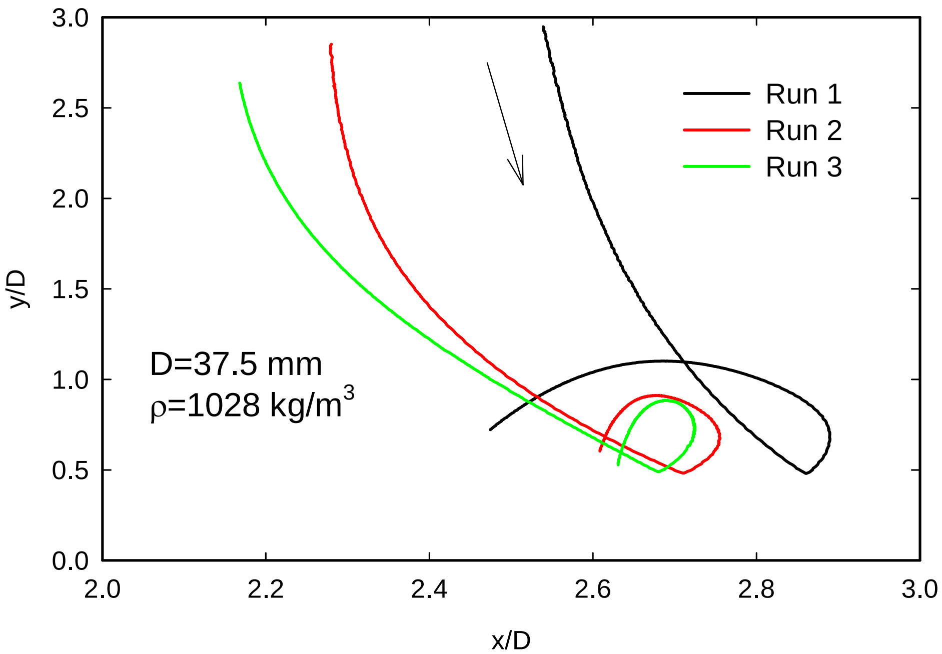

Fig.1: Non-dimensional trajectories of the plastic sphere

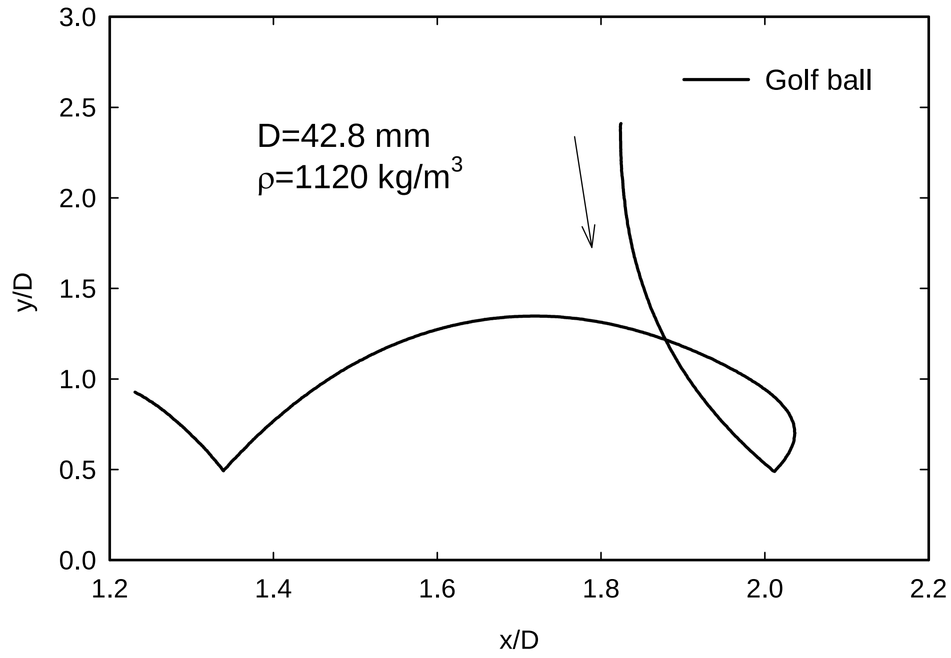

Fig.2: Non-dimensional trajectories of the golf sphere

In two positions (one is just before the impact and the second is after the impact) we calculated contours of a relative velocity magnitude. The contours of the velocity magnitude of the plastic particle (Run 1) are shown in Fig. 4. The velocities in the wake before the impact are practically the same as is the falling velocity of the particle, see Fig. 4 left. After the impact the particle moves up but the wake moves still towards the wall and the relative velocities are about two times higher compare to the falling velocity (if the restitution coefficient is close to one), see Fig. 4 right. According to the Bernoulli equation an increase in the speed of the fluid occurs simultaneously with a decrease in pressure. It means that the pressure on the left side of the particle is lower than the pressure on the right. Therefore this pressure difference probably results in an additional force that pushes the particle to the left. Similar behavior was also observed for other experimental runs with the plastic particle as well as with the golf ball.

From the experimentally determined particle trajectories the instantaneous particle velocities were calculated. The calculated velocities are shown in Figs. 5 and 6 for the vertical and the horizontal velocity components, respectively. In the time period before the impact the vertical velocities indicate an interesting behavior. When the particles fall down the vertical velocities increase but in a distance well above the bed the velocities start to decrease. This decrease of the velocity could be explained by the non-symmetrical wake formation behind the particles.

If the time series of the velocities are known, it is possible to determine time derivations of the velocities which are related to total forces acting on the particles. Examples of the time derivations of the vertical as well as the horizontal particle velocities are shown in Fig. 7 for the golf ball. In Fig. 7 the black line indicates time derivation of the vertical velocity and the red line indicates time derivation of the horizontal velocity. Negative maximum of time derivation of the horizontal velocity occurs approximately at time 0.279 sec (from beginning of the image capturing), negative maximum of time derivation of the vertical velocity occurs at time 0.379 sec. It means that the maximum forces that affect the golf ball in the horizontal and the vertical direction just after the impact do not act simultaneously. It is due to the fact that the velocity field in a vicinity of the rebounding particle is changing. Firstly the wake formed behind the particle during the falling period moves towards the bed even after the particle impact and passes the rebounding particle vertically along the left side. After that a part of the wake moves to the gap between the particle and the bed and forms a non-symmetrical velocity field in the vertical direction. This can be clarified in Fig. 8 for the golf ball.

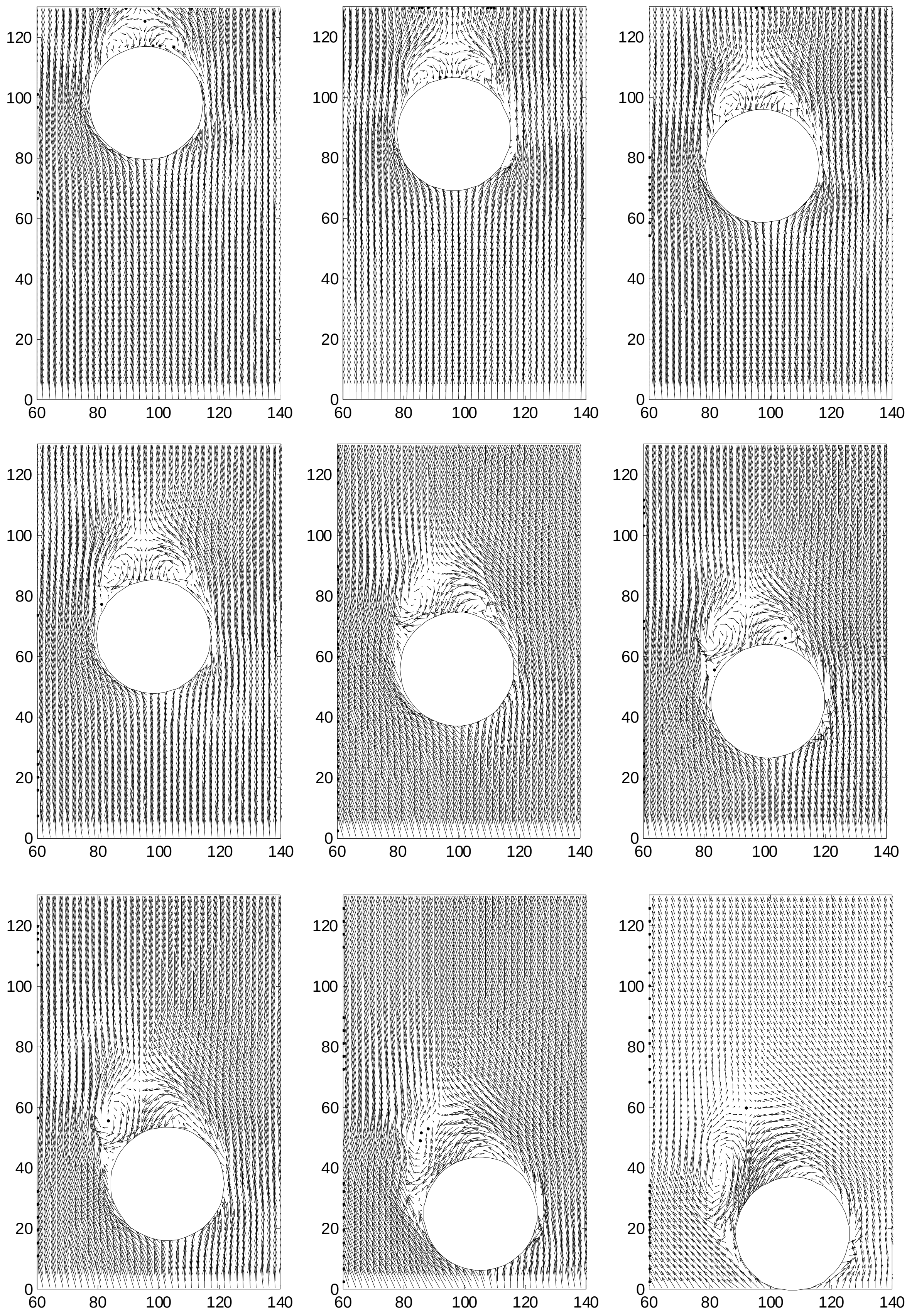

Fig.3: Wake development behind plastic sphere, D = 37.5 mm

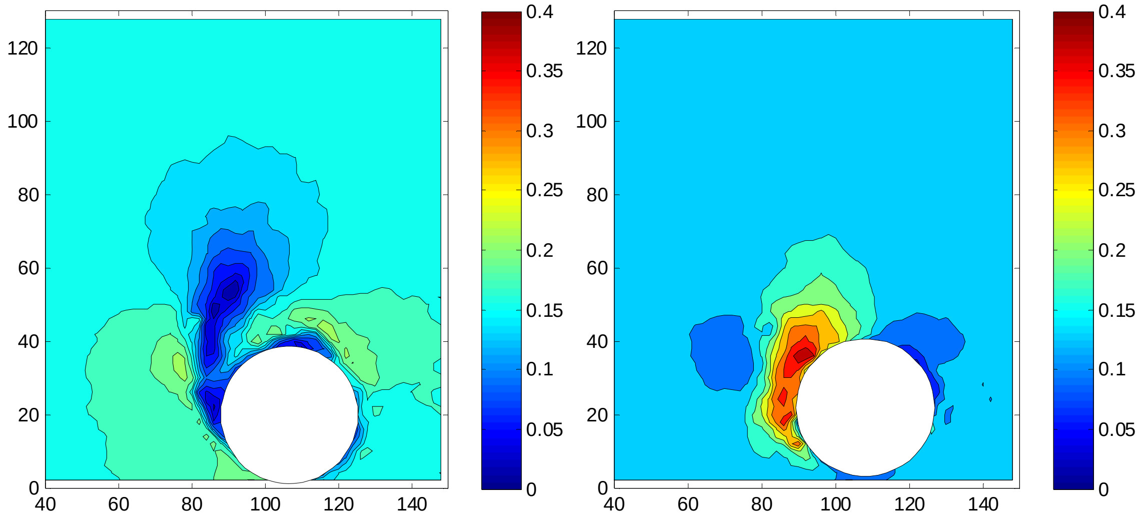

Fig.4: Contours of the velocity field captured before and after the impact of the plastic sphere

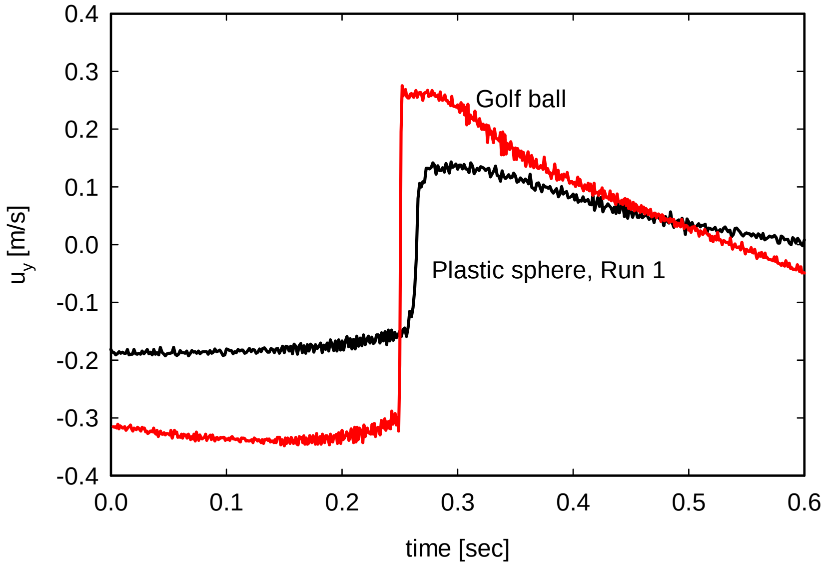

Fig.5: Vertical velocity component of the plastic sphere and golf ball

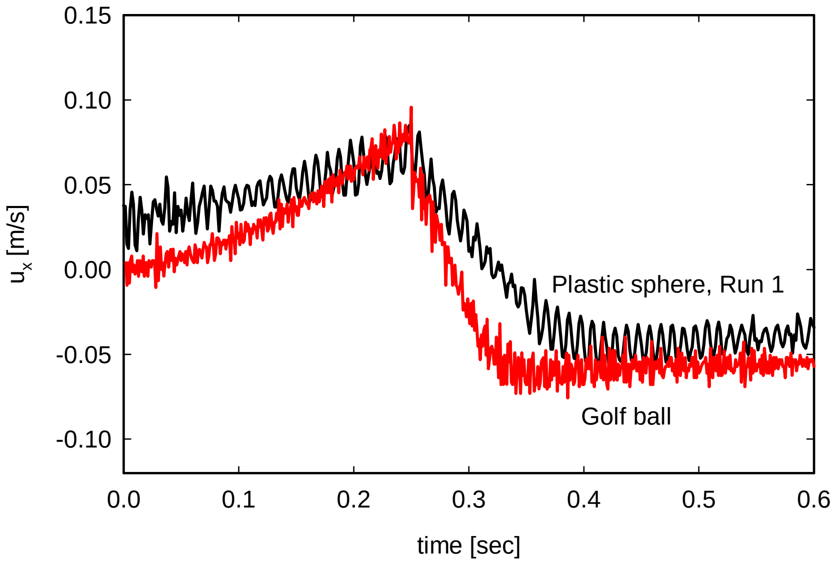

Fig.6: Horizontal velocity component of the plastic sphere and golf ball

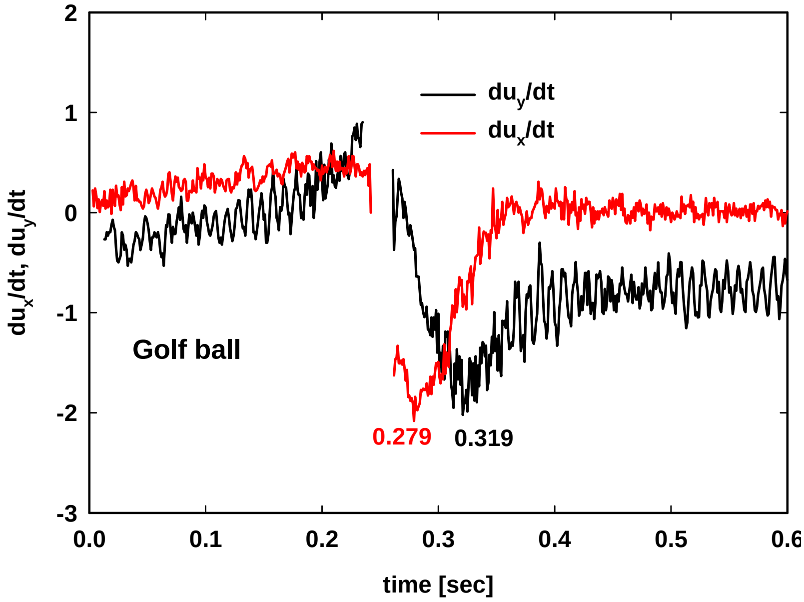

Fig.7: Time derivations of the horizontal and the vertical velocities of the golf ball

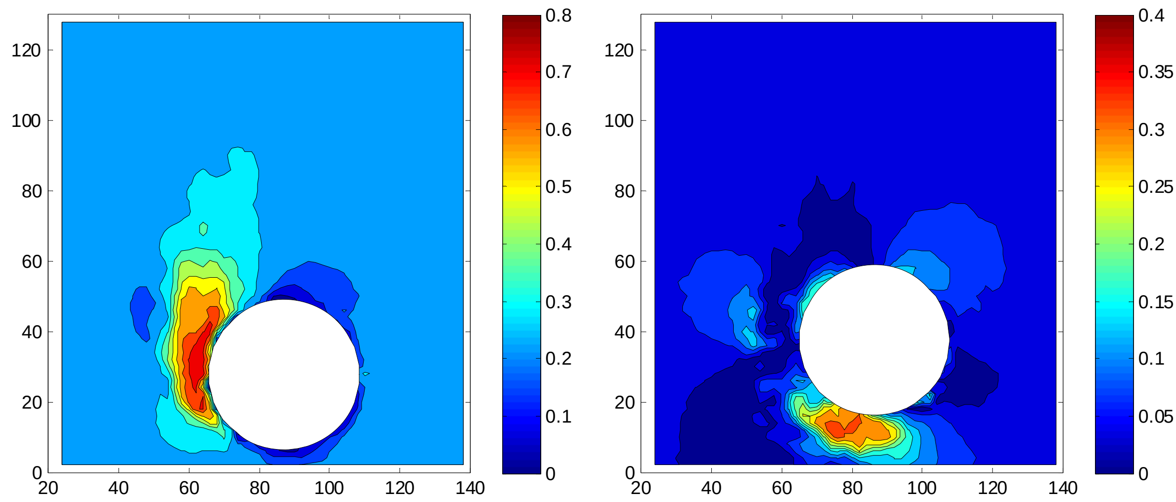

Fig.8: Contours of the vertical velocities captured in time 0.279 sec(left), contours of the horizontal velocities captured in time 0.319 sec (right) for golf ball

In Fig. 8, left, there are contours of the vertical velocity component captured in time 0.279 sec. This time corresponds to the maximum force in the horizontal direction, see Fig. 7. Fig. 8, right, shows the contours of the horizontal velocity component captured in time 0.379 sec that corresponds to the maximum force in the vertical direction. The results shown in Figs. 7 and 8 confirm the assumption that the particle movement after the impact is affected by the asymmetrical wake formed during the falling period and by the Bernoulli principle.

4. Conclusions

The movement and the impact of non-rotating spherical particles were analyzed. It was shown that there exist additional forces which act on the particles for a short time both in the horizontal and the vertical directions. These forces result from the Bernoulli principle and from a non-symmetrical motion of the wake formed behind the particles.

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