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Wake of rotating and translating sphere at low Reynolds number

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Abstract

The aim of this paper is to experimentally investigate the wake of a transversely rotated sphere at Reynolds number (Re), ranging from 250 to 400, for nondimensional rotational speed, Ω* of 0.375 and 0.5. Nondimensional rotational speed, Ω*, is defined as the ratio of maximum azimuthal velocity and free stream velocity of the sphere. PIV measurements show that flow exhibits the presence of strong shear on the upper surface at Ω*= 0.375 and Re=250 and with increase in rotational speed there is decrease in separation bubble on bottom surface. Velocity profiles for steady case at different sections in spanwise direction shows self-similarity. Vortex ring generated due to three dimensional separations from the surface of the sphere becomes unstable with small perturbations. At similar Reynolds number, but Ω*= 0.5 separated shear layer becomes unstable and shear layer breaks down into vortex rings and the phenomena repeat with time. This regime is termed as vortex shedding. The strength of the vortex rings weakens in the far wake with time. Time period of the vortex shedding remains nearly constant in the given Ω* and Re. The Strouhal number calculated in this range of Ω* and Re compares well with the reported literature.

Introduction

For three dimensional flow past a bluff body sphere is one of the foremost choices, but flow physics is far more complex, especially at higher Reynolds number when flow is unsteady. The complexity increases when rotation of the sphere is introduced. The problem of flow past a transversely rotating sphere in flowing fluid has received substantial attention due to its application in various engineering fields. Some of the major applications are in the field of combustion processes, transport of particle process, sports, atmospheric flows and many more where the spatial and temporal flow properties are important. Understanding of sphere wake in terms of vortex shedding is an important feature which has a substantial effect on turbulence enhancement. Unsteady behavior and three dimensionality in the flow are observed at lower Re also. Transversely rotating flow over a sphere attracts attention in terms of deflecting objects which is occurring due to Magnus and Reverse Magnus effect.

Incompressible flow past a stationary sphere at low Reynolds number has been studied comprehensively by Johnson and Patel [3] using experiments and numerical simulations. Upto Re=200 flow is steady and axisymmetric. For Re=210-270 flow goes into regime of steady and asymmetric. When Reynolds number is increased further flow becomes unsteady. Formation of array of hairpin vortices in the wake is observed. Howarth [2] analytically solved the problem of rotating sphere. Presence of centrifugal force generates secondary flow in the boundary layer and there is movement of fluid from pole to the equator. Giacobello et.al [1] numerically studied the effect of rotation of sphere on the wake characteristics and forces on the sphere at Reynolds numbers 100, 200 and 300. They have found transition from steady to vortex shedding at Re=250 for nondimensional rotation rate greater than 0.08. When rotation rate is greater than 0.5 at Re=300 vortex shedding is suppressed whereas it reappears at rotation rate greater than 0.80 with Kelvin-Helmholtz type of shear layer instability. At similar Reynolds number range flow past transversely rotating sphere at 0<Ω*<1 is numerically investigated Kim and Choi [4]. Various flow characteristics (steady axisymmetric, steady planer-symmetric and unsteady planer symmetric) is observed. They have observed flow to become frozen at higher rotational speed Reynolds number is increased and speed of the vortical structure is slower than the rotational speed of the sphere. Flow past transversely rotating sphere in Re range of 500-1000 has been studied using direct numerical simulation by Poon et al. [5] for varying Ω* ranging 0 to 1.2. They observed three-flow regimes viz. vortex shedding, shear layer instability and shear layer–stable foci. Observed stable focus region on the onset of shear layer instability increases the unsteadiness in the flow and RMS pressure increases. Stable focus becomes more pronounced at higher Re and Ω*. The effect of moderate to high Reynolds numbers on flow past a sphere in uniform flow was analysed experimentally by Sakamoto & Hainu [6]. Stewart et al. [7] numerically and experimentally studied wake of a rolling sphere. Forward rolling shows behaviour of isolated sphere at different Re including vortex shedding at higher Re whereas reverse rolling shows formation of two distinct vortex from sides. There is very little information available in literature for translating and rotating sphere in quiescent fluid at low Reynolds number. Present study aims to find the two-dimensional flow features for transversely rotating and translating sphere in quiescent fluid.

Experiments

The experiments are conducted at moderately high Reynolds numbers in the glass channel of dimension 2 X 0.14 X 0.17 m^3. A long slotted aluminium piece is placed on bottom wall along the length of the channel at mid height. A sphere is fitted to one end of a shaft whereas other end of a shaft is connected to a cylindrical roller (diameter of 16 mm) which can roll under gravity along the track when the inclination of the channel is changed. When roller rolls over the track the sphere experiences rotational as well as translational motion. Sphere rotates about z-axis with a rotational speed, ω and translational speed U_∞ as shown in Fig. 1. In present experiments we have used two spheres of diameter 6±0.01mm and 8±0.02mm to obtain various Reynolds number and nondimensional rotational speed, Ω*. Nondimensional rotational speed can be represented as the ratio of diameter of the sphere (d_s) and of the roller (d_r), $\Omega^* = d_s/d_r$. Long length of the channel helps the sphere to achieve the terminal velocity for steady flows. For unsteady flows there are fluctuating forces due to vortex shedding, so there is small fluctuation in the velocity of the sphere. However by larger mass of the cylindrical roller reduces the fluctuating force. Test section is located 1.5m downstream of the starting point of the sphere motion. Particle image velocimetry (PIV) measurements carried out to capture the flow characteristics in the wake of the sphere. Water in the channel is seeded with 10 µm silver-coated glass particles which are illuminated using a light sheet in the x-y plane created from a 2 Watts, 532 nm green coloured Continuous Diode Pulse Solid State Laser (DPSS). Flow images are recorded using a Photorn high-speed camera at the rate of 2000 frames per second. The captured images are analysed using PIV lab software to obtain the information of flow field [8].

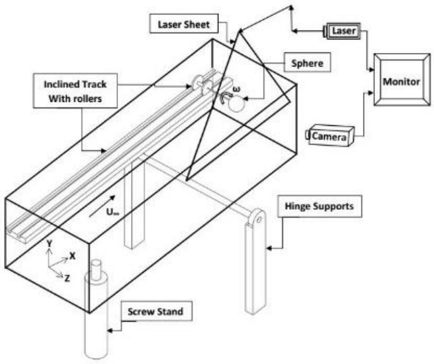


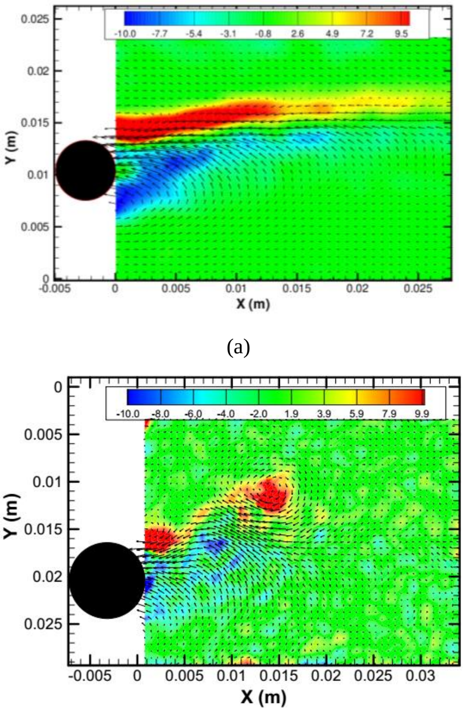
Figure 1. Sketch of rotating and translating sphere experimental set up

Results and discussion

Aim of the present experiments is to understand the flow characteristics and vortex dynamics in the wake of rotating and translating sphere in quiescent water at low Reynolds number range 250 to 340 using the PIV measurement data. The roller Presence of the small rod supporting the sphere is neglected here. The steady and unsteady flow regimes in terms of vorticity, velocity and stream function in the wake of sphere are analysed and presented.

(a) Re = 250, Ω* = 0.375, 0.5

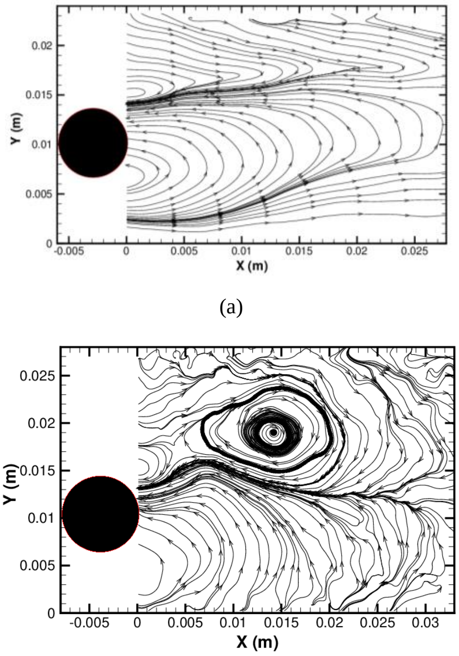
Figure 2 shows superimposed velocity and vorticity variation in the flow field when sphere has just moved out of the field of view. It is to be noted that for all the experiments sphere is moving from right to left. As sphere is not transparent the flow field is shown in the instant when sphere has just moved out. It is clear from figure 2(a) that the flow is nearly steady on the upper part of the sphere for Ω* = 0.375. The attached vortical structure enveloping the sphere is non-axisymmetric. Stream lines shown in figure 3(a) shows steady behaviour like the case reported for stationary sphere by Johnson and Patel (1999) where it is seen that flow remains steady and non-axisymmetric at Re range 210 to 270. The thin shear layer is visible in the streamline plot. Non-axisymmetric nature of wake is present due to rotation. On the bottom side wake still remains steady and bubble size is small. The large velocity vector in the direction of movement of the sphere at near wake indicates some of the fluid is dragged with the sphere. Change in Ω* to 0.5 causes clear transition from steady to unsteady and large vortex is shed from the top (Figure 3b). Rotation reduces the extent of adverse pressure gradient on bottom and increases the same on the top. Velocity profile in the wake is plotted at different sections in the wake (Figure 4). Normalized u velocity with local maximum velocity at different sections corresponding to the case (Re=250 and Ω* = 0.375) shows collapsing of data on same curve showing the similarity of the velocity profiles at t=1.014s. t=0s is the time when sphere enters the field of view of recording area. Variation of the u and v velocity in the streamwise direction along the centre of the sphere is shown in figure 4 (b) and (c).



(a)

(b)

Figure 2. Instantaneous vorticity contour with super imposed vectors for Re =250 (a) Ω^* =0.375 (b) Ω^* =0.5



(a)

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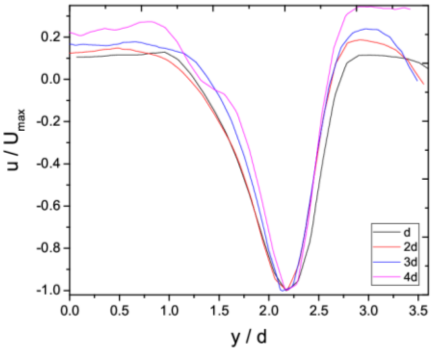
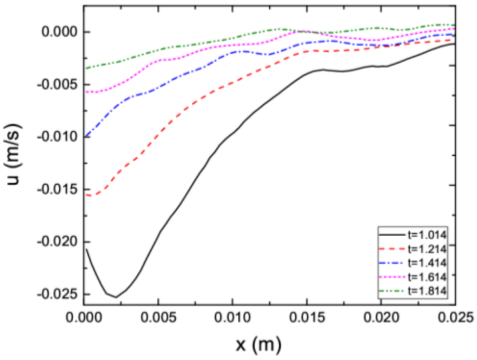
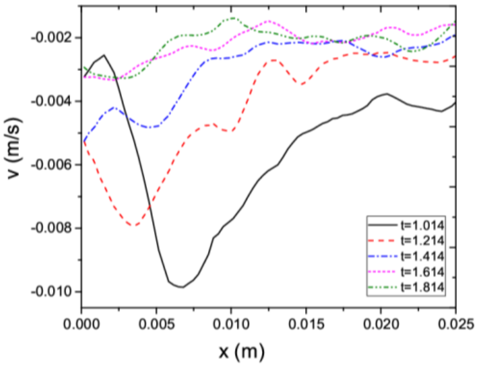
Figure 3. Streamlines plotted for Re = 250 and (a) Ω^* =0.375 (b) Ω^* =0.5



(a)



(b)



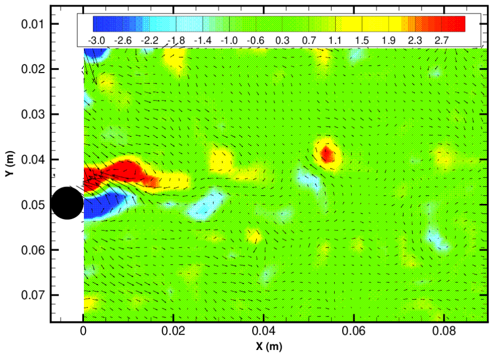
(c)

Figure 4. (a) Normalized u-velocity at different distances from left end. (b) u and (c) v velocity in the streamwise direction for steady case at Re = 250 and Ω^* =0.375.

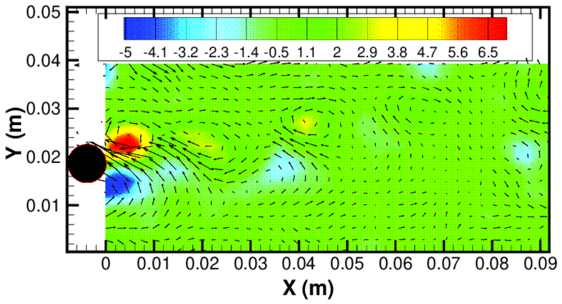
Streamwise velocities at t=1.014s shows the decrease in velocity from near to far wake. With time more drop in velocity shows the dissipation into the surrounding fluid.

(b) Re = 305, Ω* = 0.375, 0.5

When Reynolds number is increased to 305, at lower rotation rate (Ω* = 0.375) flow regime changes to unsteady from steady (figure 5a). In unsteady regime shear layer becomes unstable to disturbances of larger wavelengths and vortex rings are formed. Appearance of vortices of opposite signs in two dimension is indication of vortex ring. When rotation rate is more vortex shedding becomes clear (figure 5b). However strength of the vortex decreases with time in the far wake and in the near wake it is maximum. As there is strong dissipation with time vorticity contours are not visible in the far wake. However streamline plot in figure 5(c) clearly identifies the vortices present in the flow. Existence of stable focus is also visible.



(a)



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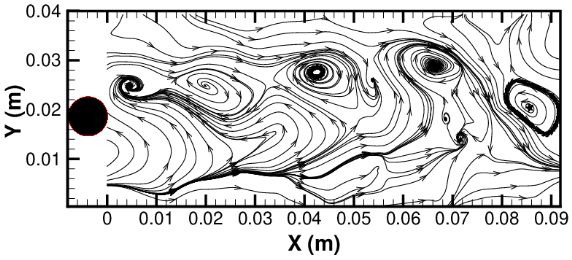


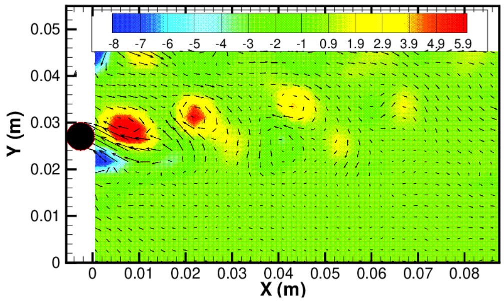
(c)

Figure 5. Instantaneous vorticity contour with superimposed vectors for Re =305 (a) Ω^* =0.375 and (b) Ω^* =0.5, (c) streamline plot figure 5(b).

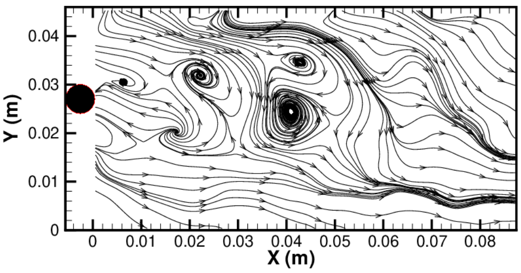
(c) Re=400, Ω* = 0.375, 0.5

With increase in Reynolds number to 400, more structured vortex shedding type flow is observed. Figure 6 shows the vorticity contour and streamlines for Ω* = 0.375. Counter rotating vortices in pair indicates formation of vortex rings. With increase in rotation rate near wake shear layer becomes unstable and forms shear layer shedding but a little in the far wake regular vortex shedding flow as observed by Poon et al. [5] is seen (Figure 7). Higher rotation rates leads to increase in the width of the wake. It is now clear from figures 6 and 7 reduction in vortex strength in streamwise direction from near to far wake. Unlike the cases of rotating sphere in freestream flow where small wavelengths becomes unstable and forms smaller structures, here vortices decays by dissipating energy to the surrounding fluid. Spanwise velocity distributions at different sections shown in figure 7c depicts that velocities are not self-similar at higher Re compared to steady state case. There is movement of the vortex also in spanwise direction.

Nondimensional vortex shedding frequency seems to be nearly a constant for all cases in the Re ranging between 270 and 400. Figure 8 shows the Strouhal number ($St=fd/U_\infty$, where f is the frequency of the instability vortex, *d* is diameter of sphere) variation with Re for different rotation rates. Even though there is little increase with Re at smaller rate, it is nearly constant around 0.25.

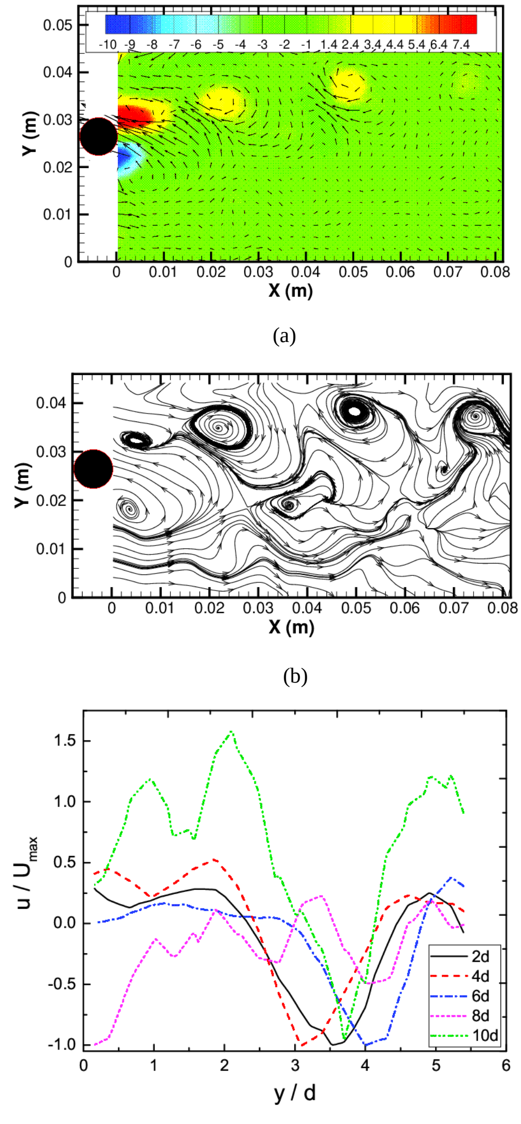


(a)



(b)

Figure 6. (a) Instantaneous vorticity contour superimposed with velocity vectors and streamlines at Re = 400 and $\Omega^* = 0.375$



(a)

(b)

(c)

Figure 7. (a) Instantaneous vorticity contour superimposed with velocity vectors and (b) streamlines (c) spanwise velocity distribution at different section for Re = 400 and $\Omega^* = 0.5$.

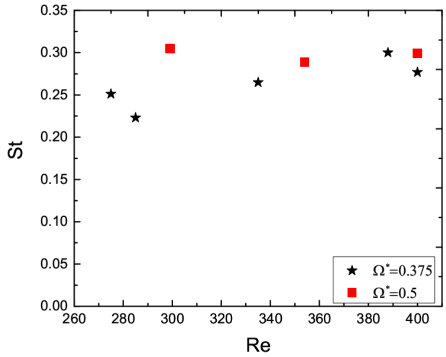


Figure 8. Variation of the Strouhal number at Re ranging from 270 to 400

Conclusions

The flow past a transversely rotating and translating sphere in a quiescent water at Reynolds number range 250 to 400 for various rotational rate has been analysed experimentally. At Re=250 and nondimensional rotation rate flow shows steady behaviour past the sphere with self-similarity of the streamwise velocity in the wake. With increase in rotation rate flow becomes unsteady with the formation of vortex rings in the wake. At higher Reynolds number and rotational rate, array of vortex rings are formed and strength of vortices decreases in streamwise direction from near to far wake.

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