The wake behind a rotating sphere

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Abstract. The wake behind an axisymmetric body rotating about an axis aligned with the streamwise direction has been experimentally investigated in a low-velocity water channel for the intermediate Reynolds number. The measurements focused on the evolution of the flow regime with two counter rotating vorticies, as a function of two control parameters, namely the Reynolds number and the dimensionless rotation rate Ω.

1. Introduction

The wake behind different 3D static bodies e.g. sphere, disk, cube etc. were considered in the numerical as well as experimental studies. The flow of a viscous fluid past a rotating sphere may be considered as a simplified case of a general family of immersed axisymmetric body flows with widespread applications. Therefore the investigation of the wake behind a rotating sphere is a main objective of this paper, as understandig the effect of rotation in more complicated flows (e.g. wind turbines) becomes easier.

The direction of rotation has significant influence on the characteristics of the flow over a sphere. Two particular directions of rotation can be specified. The first one is orthogonal to the streamwise direction. In this case researches on the so-called Magnus or Robins effect (Barkla & Auchterlone [1]) were focused on the determination of the lift and drag force. The other case is the rotation of the sphere parallel to the streamwise direction. Most of works (Kim and Choi [4]; Pier 2012; Poon et al. [6]) focused on forces (lift and drag) acting on a rotating sphere depending on the values of free stream velocity and the rotational speed. However, these investigations were undertaken only numerically. The influence of rotation direction on the wake was presented by Poon et al. [6]. The simulations were performed for the Reynolds number 100, 250 and 300 and for the non-dimensional rotational rate Ω = 0.05 - 1. The angle of axis of rotation with respect to the streamwise direction varied between 0 and 90 degrees. The steady and unsteady flow regimes were indentified. In present paper the sphere rotating about an axis aligned with the streamwise direction was considered.

These flow instabilities and the bifurcations in the wake past a static sphere (Ω = 0) are well known now from previous reasearch (both experimentally and numerically). The first three regimes can be distinguished: axisymmetric basic flow, planar symmetric flow with two steady counter rotating vorticies and the flow with unsteady periodic hairpin shedding preserving symmetry plane. Subsequent bifurcations appear for the critical Reynolds numbers $Re_1 = 212$ and $Re_2 = 272$ (Johnson & Patel [3]; Gumowski et al. [2]). The flow regimes, observed...
numerically, for the rotating sphere, parallel to the streamwise direction, significantly differ from
the static configuration. The wake becomes “frozen” for specific Re and Ω for steady as well as
for transient flows (Kim & Choi [4]). For the steady planar symmetric flow with the counter-
rotating vortices one of the vortical structures becomes stronger, while the second is weakened,
as an effect of rotation. This phenomenon was demonstrated by Kim and Choi. They have
established the frequency of complete of the revolution vortical structure as a function of the
rotation rate Ω as well as the Reynolds number. Pier [5] numerically identified the subsequent
flow regimes (i) an axisymmetric steady base flow (either stable or unstable) (ii) low-frequency
periodic helical, (iii) quasi-periodic shedding and (iv) high-frequency periodic helical.

The main purpose of the present paper is to present results of experimental investigation
the effect of the streamwise rotation on the characteristics of flow past a sphere as a function of
Reynolds number. Of particular interest is the influence the rotation rate Ω on the vorticity in
the wake as well as the existence of different flow regimes. (The rotation rate Ω is defined as a ratio
of the maximum azimuthal velocity of the rotating body and the free stream velocity.) These
results are to be confronted with earlier numerical investigations. However, the experiment itself
is quite difficult to prepare as minimum intrusive system allowing the rotation of the sphere is
needed (the same system should also serve as a sphere support as well as to deliver the colorant).
This is further discussed in the text.

2. Experimental set-up
The research was carried out in a low-velocity water channel using LIF (Laser Induced
Fluorescence) visualization and PIV (Particle Image Velocimetry) method. The cross-section of
the channel was 10 × 10 cm. The length of the test section was 86 cm. The diameter of the
investigated sphere was 2 cm. The range of investigated velocities was between 0.4 and 4 cm/s,
while the corresponding Reynolds number was between 80 and 800. The supporting system is
shown in Figure 2.

An angular velocity of the sphere was controlled with high accuracy thanks to the use of
brushless electric motor. As it was mentioned the most difficult problem to resolve was to design
the rotational system without significantly perturbing the flow. It was required to achieve the
rotation as well as injection the colorant for the visualization at the same time. To protect the
motor against water and damage a special cover with seals was manufactured. The motor was
placed inside the water channel at the considerable distance (1 meter) upstream from the test
section. The torque was transmitted by 3 mm carbon fiber tube with high stiffness to reduce
the possibility of vibrations. All parts were assembled using laser pointer to maintain coaxiality.
The investigated angular velocity was 0-200 rpm. The full setup is shown in Figs. 1, 2 and 3.

2.1. Visualization
To perform visualization of the flow on the rotating device special treatment have been made
(Figure 3). The dye (fluorescein dye in solution) was injected through a small hole in the middle
of sphere (see Fig. 3). Additional dedicated parts were manufactured in order to resolve the
difficulties of the dye injection simultaneously with the rotation. The fluoresceine is delivered
from the external reservoir to the rotating sphere: by (i) the silicone tube, in (ii) the steel tube
to the small bullet shape body, then (iii) into the rotating perforated tube, next outside of the
bullet shape body in the steel tube and (v) at the end to the sphere. Special seals have been
used to prevent leaks between the rotating axis and the non revolving part of the bullet shape
body.

2.2. PIV
2D Particle Image Velocimetry method was used with purpose to obtain quantitative data related
to the flow behind the rotating sphere. It is a well-known, non-intrusive, optical and indirect
measurement of two in-plane velocity components of the investigated flow field. The water was seeded with tracer particles with mean diameter size 11 µm. The particles were carried by the fluid and their position was determined by illumination with the laser sheet and captured by a high-resolution digital camera. Two orientations were used in this paper: the back view orthogonal to the streamwise direction and the side view parallel to the streamwise direction.

Figure 2. Waterproof cover with electric motor.

3. The experimental results
The measurements focused on the identification of the flow regimes that appear depending on the values of two control parameters, namely the Reynolds number $Re = \frac{v_\infty d}{\nu}$, where $d$ is the diameter of the sphere, $v_\infty$ - free stream velocity, $\nu$ - kinematic viscosity while the dimensionless rotation rate $\Omega = \frac{\Omega}{v_\infty}$. The rotation rate $\Omega$ is defined as a ratio of the maximum azimuthal velocity of the rotating body and the free stream velocity.

The flow past a rotating sphere was investigated for different Reynolds number but here is presented for the most representative $Re = 250$ to concentrate on an initial regime of flow instability. The axis of rotation was parallel to the streamwise direction and the non-dimensional rotational speed $\Omega$ remained in the range 0-1. The present study focuses on the modification

Figure 3. The visualization system.
of vortical structures behind the sphere. As explained below, the experimental results confirm that the flow characteristics highly depend on the rotational speed.

![Instantaneous streamwise vorticity fields](image)

**Figure 4.** Instantaneous streamwise vorticity field obtained from PIV - the clockwise rotation and the counter clockwise rotation.

![Visualization of the flow](image)

**Figure 5.** Visualization of the flow a) side view, b) back view and back view vorticity field (PIV results) for Re = 250

Firstly, we observed the influence of sign of rotation on the flow characteristic. There are two opposite sign of rotation: clockwise rotation vs. counter clockwise rotation, let is determined as a negative and a positive respectively. The streamwise direction of rotation with a constant angular velocity was taken into consideration. In Fig. 4 there are presented instantaneous streamwise vorticity fields $\omega_x$ for case of static sphere ($\Omega = 0$), rotating sphere in both directions with $\Omega = \pm 0.2$ and with $\Omega = \pm 0.3$. In the first picture the regime of two counter vorticities with
planar symmetry is visible. The red color corresponds a positive values of vorticity, the blue to
the negative. In the next picture it is shown that the negative vorticity becomes weaker (blue
area is smaller than in the first picture) while positive $\omega_x$ becomes stronger (red one is bigger).
This is caused by a positive rotation of the sphere. In the middle picture the same effect is
present. In this case the negative vortical structure is enhanced due to negative rotation. The
next two pictures confirm this effect. The influence on vortical structures caused by the rotating
of the body is symmetric with respect to the sign of the rotation. Neither positive direction
nor negative is specified. Therefore, from this point we will consider only positive direction of
rotation of the sphere without loss of generality.

Figure 5 presents the changes in the flow caused by the rotation of the sphere at $Re = 250$ with
flow visualization as well as PIV. In the static case ($\Omega = 0$) a pair of vortices in opposite direction
appears in the wake. It is confirmed in the first row containing side view flow visualization, back
view visualization and back view PIV results. At $\Omega = 0.2$ one of two vortices becomes bigger
while the other is disappearing. At $\Omega = 0.4$ one can see that the flow becomes helical. The
effect becomes stronger with the bigger $\Omega$. The second column presents back view visualization
(fluoresceine dye induced by laser sheet in a cross section ortogonal to the flow near the sphere).
Based on this method of visualization one can notice that the flow becomes periodic for small
$\Omega$. Observed modifications caused by rotating sphere based on visualization can be confirmed
by PIV results (Fig. 6).

![Figure 5](image1.png)

**Figure 5.** Time-space extracion of the longitudinal vortical structures behind a rotating sphere
as a function of $\Omega$. PIV results for $Re = 250$

Figure 6 shows the two-dimensional vortical structures expanded in time behind a stationary
sphere and rotating sphere at Reynolds number of 250. The surfaces of vortical structures
are identified using the method of longitudinal component of imaginary part of the complex
eigenvalues of the gradient velocity tensor and this allows comparison with numerical results.
The diagrams was colored by the value of vorticity. The red color corresponds to positive value of vorticity, the blue color to the opposite one. Again, without rotation in the wake a pair of vorticies appear with the same vortical strength but opposite direction of rotation. At $\Omega = 0.1$ the vortical structure with positive $\omega_x$ becomes stronger but that of negative $\omega_x$ becomes weaker. This can be explained by the fact that rotation of the sphere induces positive streamwise vorticity in the wake. At the $\Omega = 0.3$ the negative vorticity almost disappears in the wake. However, the structure with negative $\omega_x$ appears again in the wake for $\Omega \geq 0.5$. This effect was described in the numerical research (Kim and Choi [4]; Pier [5]) and thus it is confirmed by experiment. The vortical structures with positive and negative sign are strongly twisted together for larger values of $\Omega$.

![Graph](image)

**Figure 7.** Time for the vortical structure to complete one revolution normalized by the time for the sphere to rotate by $2\pi$ and time of second observed frequency normalized.

We have studied also the temporal behavior of such flows, following the Fourier spectra of the transversal velocity field. Figure 7 presents the main frequencies obtained from fourier decomposition, as a function of $\Omega$ for $Re=250$. We observe two main scenarios: for small $\Omega$ the unsteadiness is related to the frozen vorticity rotating with the sphere while for the intermediate $\Omega$ there appears a new temporal instability. This phenomena are at present under further investigation.
4. Conclusions
Laminar flow past a sphere rotating in the streamwise direction was experimentally investigated. The research was performed at $Re = 250$ and in the range of $0 \leq \Omega \leq 1$. The results showed that the flow strongly depends on rotational speed. Rotation of the sphere induces positive streamwise vorticity in the wake and this causes weakening of the negative vortex while the flow becomes periodic and helical.

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