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Investigation of Flow past a Rotating Cylinder

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Abstrakt: *The paper deals with results of experimental and numerical investigation of a rotating circular cylinder. Two dimensional incompressible laminar flow at Reynolds number Re = 100 is studied in the region of non-dimensional rotation rate $0 \leq \alpha \leq 5.3$. Different flow structures were observed – Shedding Mode I, stable region, Shedding Mode II, and another stable region. Experimental research was performed in a towing tank that is filled with water and the rotating circular cylinder was moved horizontally along the tank. Applied measurement technique was the PIV method. Vortex structures behind the rotating circular cylinder were observed and captured in the region of Shedding Mode I and Shedding Mode II. There are no vortex structures in stable regions. Numerical simulations of flow past a rotating circular cylinder were performed by means FLUENT Code. The existence of first and second instabilities was proved numerically by means of time history of lift coefficient c_L. Achieved numerical and experimental results are in a good agreement with available literature.*

1. Introduction

Experimental and numerical investigations are focused on the flow behind a circular cylinder rotating with a non-dimensional rotation rate α varying from 0 to 5.3 in a towing tank that is filled with water. This rotation rate range covers different flow regimes, such as Shedding Mode I, a stable region, Shedding Mode II and then another stable region. The measurements were performed for Reynolds number Re = 100.

The experimental part was conducted in collaboration with Mechanical Engineering Department at University of Technology (TU/e) in the Netherlands. Particle Image Velocimetry (PIV) technique was used in a towing tank to perform this investigation. PIV analysis of the images was done using PivView and PivTec software. The post-processing of the results was analyzed with Matlab software.

The numerical part was developed at Czech Technical University (CTU) in Prague. A commercial software by ANSYS company was used for calculations. This software is installed on computers based at the university.

2. Methodology

The flow field is characterized by two parameters, the Reynolds number Re and the rotation rate α:

$$Re = \frac{U_\infty D}{\nu} \qquad (1)$$

$$\alpha = \frac{D\omega_c}{2U_\infty} \qquad (2)$$

Here U_∞ is the free-stream velocity, D the cylinder diameter, ν the kinematic viscosity, ω_c the angular velocity of the rotating cylinder. The next important non-dimensional parameter is the Strouhal number *St*:

$$St = \frac{f_{shed} D}{U_\infty} \qquad (3)$$

where f_{shed} denotes the shedding frequency. The value of Strouhal number depends on the rotation rate.

The experiments were conducted in a towing tank with dimensions $L \times W \times H$ = 500 cm x 50 cm x 75 cm. The experimental configuration consists of a circular cylinder with a diameter D = 10 mm.

The cylinder is placed between two parallel square plates with width of 200 mm that have bearing function. The length of the cylinder is *l* = 480 mm and its position is in the middle of the water level in distance 30*D* from the bottom wall of the tank. The cylinder rotates in the counter-clockwise direction with angular velocity ω_c. The rotation rate α is changed by setting the voltage of the electric motor. Two cameras are positioned on the side of the tank to record images. The cameras, cylinder and electric motor are fixed to a carriage system which is placed on the top of the side walls. It moves from right to left. The speed of the carriage corresponds to the free-stream velocity U_∞.

ANSYS Gambit 2.4.6 was used for geometry and mesh creation. The quad mesh consists of quadrilateral elements. Number of cells is 305 100. The domain is divided into blocks where structured grid and multi-block grid are used. The geometry consists of a counter-clockwise rotating cylinder with diameter *D* = 10 mm and a rectangular domain with dimensions 45*D* x 30*D*.

Fluent 6.3.26 was used for calculations. The flow medium - water - enters on the left side to the rectangular domain where Velocity inlet condition with a constant free-stream velocity U_∞ = 10.047 mm.s^{-1} is selected. It gets out on the right side from the rectangular domain where Pressure outlet condition is *p* = 0. Upper and bottom sides are Symmetry. The cylinder with diameter *D* = 10 mm is defined as Moving Wall with rotation speed n.

The viscous model is laminar. Pressure-based solver was developed for low-speed incompressible flow. It is used for calculations with Implicit formulation. Second-order upwind scheme was set up. QUICK (Quadratic Upwind Interpolation for Convective Kinematics) convection scheme is implemented in Fluent. This scheme showed better results than second order scheme. Fractional Step is used. A flow is unsteady with time step Δt = 0.025 s.

Vortices were estimated by means of the lift coefficient [1]:

$$C_L = \frac{2F_L}{\rho V^2 A} \quad (4)$$

Vortex shedding around rotating cylinder causes periodic changes in velocity and pressure field. Therefore lift force is not constant, but it has amplitude periodic component with frequency f_{shed}. This frequency corresponds to the Strouhal number. Contrary flow without vortex shedding causes constant lift force and f_{shed} is equal to zero.

The vorticity components for two-dimensional flow in x-y coordinate system can be written in form as [2]:

$$\omega_z = \frac{1}{2}\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) \quad (5)$$

3. Results

The von Karman vortex street (Figure 1) is seen in the wake behind the cylinder for $0 \le \alpha \le 1.8$ with *St* ~ 0.165 and this regime is called Shedding Mode I (Figure 2). Negative vortex is shed from the upper surface of the cylinder while a positive vortex is released from the lower surface. The vortices are axially symmetrical for a non-rotational case.

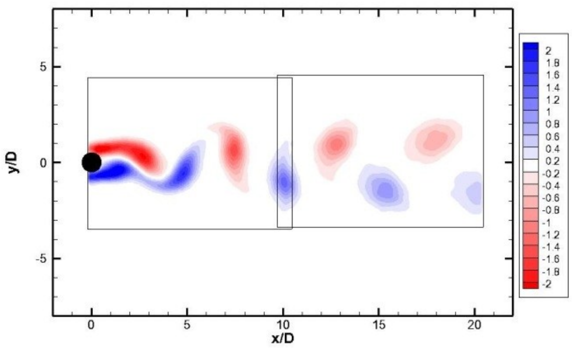

Figure 1 – Von Karman vortex street, α = 0, Re = 100

An increase in the rotational rate is accompanied by an upward deflection of the wake. Therefore, the vortex street is deflected away from the centre line for a non-zero α and due to the counter-clockwise direction of the rotation. The wake becomes wider and the Strouhal number for the vortex shedding slowly decreases with the increasing rotational rate. The experimental Strouhal number at α = 1.6 is St = 0.164 and numerical is St = 0.158. The vortex shedding ceases beyond α ~ 1.9 for Re = 100.

A steady state at α = 3.0 is achieved with increasing α and is found between two unstable regions (Figure 3). The vortex shedding is completely suppressed. The Strouhal number is equal to zero. It is in accordance with the experimental and numerical solution. One numerical calculation was done also at α = 4.65 where Strouhal number is St = 0.

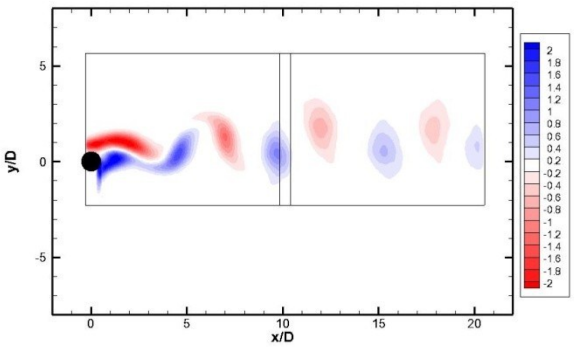

Figure 2 – Shedding Mode I, α = 1.6, Re = 100

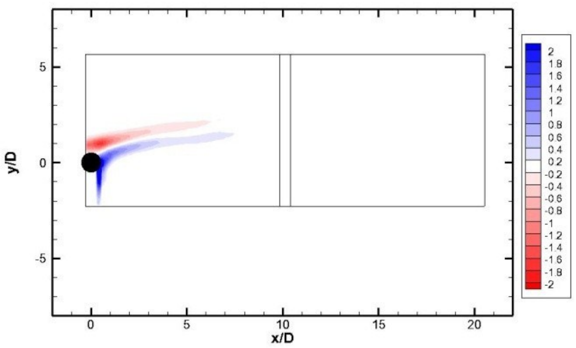

Figure 3 – Stable region, α = 3.0, Re = 100

The flow loses its stability at α ~ 4.8. The second type of instability appears for higher rotational speed at α = 5.08, 5.12, 5.21 for the experimental measurements (Figure 4) and at α = 4.80, 4.90, 5.0, 5.2 for the numerical calculations. This region is called Shedding Mode II. The vortex shedding appears again but as a single shed vortex in a counter-clockwise sense. The vortex appears only from its upper surface and so on the instability is different than in Shedding Mode I. In the experiment, four vortices are developed during one measurement at α = 5.08, 5.21 and three vortices at α = 5.12.

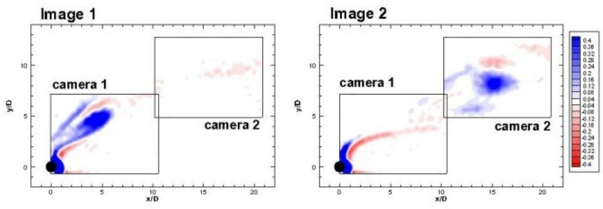

Figure 4 – Shedding Mode II - α = 5.08, Re = 100

The existence of vortices was proved using the lift coefficient cL in numerical computations (Figure 5). An oscillating curve is seen at α = 0 and α = 1.6. When vortices are suppressed at α = 3.0, the time history of the lift coefficient goes to the constant value cL = - 0.1023. It starts again to oscillate at α = 4.8 until α = 5.2. The values of cL decreases with increasing rotation rate (Figure 6).

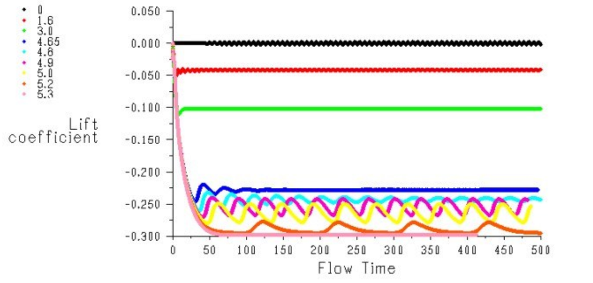

Figure 5 – The time history of the lift coefficient

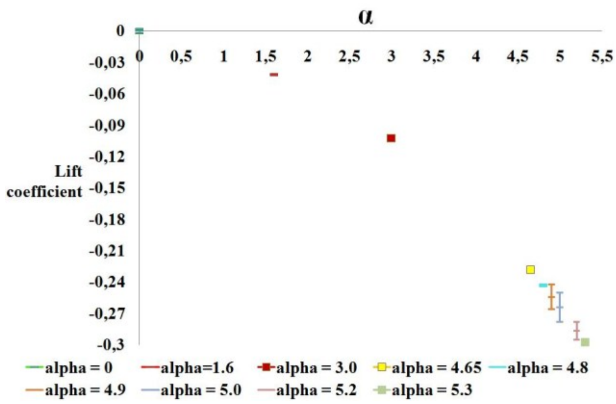

Figure 6 – Lift coefficient versus rotation rate

4. Discussion

Dependence of rotation rate α and Strouhal number St is seen in Figure 7. Comparison of experimental measurements (blue colour), numerical calculations (red colour) and study by Akoury et al. (2008) [3] (green colour) is shown. Overall, current results are moved to the lower values. It is caused by standard deviation in experiments or calculations. Another researches of these regimes – Shedding Mode I, Stable regions and Shedding Mode II - at Re = 100 were by Stojkovic et al. (2003) [4], Pralits et al. (2010) [5] or Sharma et al. (2010) [6]. Results of current measurements and computations are in a very good agreement with them.

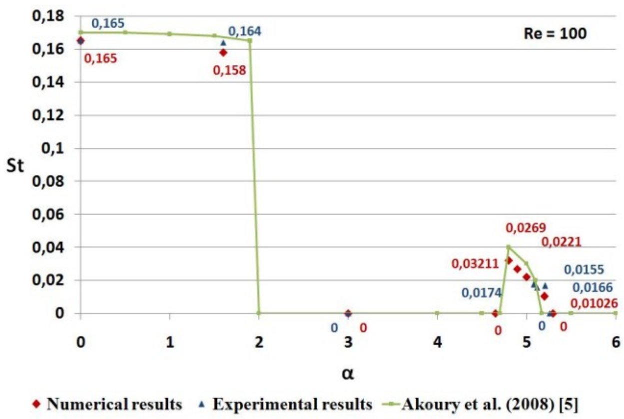

Figure 7 – Comparison of experimental and numerical results – *α* versus St

5. Conclusion

Experimental measurements and numerical calculations were done at Re = 100 for α varying in range of $0 \leq \alpha \leq 5.3$. This rotation rate range divides flow into several regimes, such as Shedding Mode I, a stable region, Shedding Mode II and another stable region. Results are in a very good agreement with previous literature [1, 3, 4, 5, 6]. For more details see diploma thesis by Balcarová (2011) [7].

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