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Triggering vortex shedding for flow past circular cylinder by acting on initial conditions: A numerical study

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ABSTRACT

Physically, when the Reynolds number exceeds some critical value, vortex shedding past a circular cylinder appears naturally and immediately. Numerically, if the domain geometry and the approaching flow conditions are symmetric, vortex triggering requires a long run-time, especially for low Reynolds numbers. The present study proposes to reduce this run-time by acting on the initial conditions instead of the classical approaches based on boundary conditions perturbation. In contrast to these, the proposed technique does not bring any energy to the flow. The vortex shedding is simply triggered by introducing a lateral gradient to the initial streamwise velocity. Simulations are performed using the ANSYS CFX 12® finite-element-based finite volume code. A two-dimensional laminar flow at Re = 100 is first considered. Without perturbing the initial uniform flow, the obtained results are in good agreement with the experimental and numerical results available in the literature. With perturbed initial conditions, the main characteristics of the flow are properly found while the run-time required for triggering the ultimate regular periodic regime with vortex is considerably reduced. Simulation results show that the extent of the run-time reduction depends on the amplitude of the initial perturbation. The search of the optimal value corresponding to the largest run-time reduction led us to propose an analytical expression by assuming that the natural vortex shedding frequency is equal to the periodic lateral perturbation frequency. The validity of the expression was verified for Re = 100 and confirmed for Re = 60, 80 and 120. It was then used to perform many simulations in a reasonable time. All obtained results show that the proposed technique gives better results compared to the impulsive start technique and better mimics the physical reality, at least for low Reynolds numbers.

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1. Introduction

Fluid flow past a circular cylinder is an important phenomenon that appears in many engineering applications such as energetic, industrial, civil, and environmental process. The flow configuration is controlled by the Reynolds number $Re = U_\infty \cdot D/\nu$, where ν is the kinematic viscosity of the fluid which is moving with free-stream velocity U_∞ and D is the cylinder diameter. When the Reynolds number of the flow exceeds a critical value, the unsteady separation of flow around the cylinder starts creating vortices which detach from each side of the cylinder surface and move downstream in a repeated pattern of swirling vortices: the von Karman vortex street.

Because of the critical Reynolds number importance, many experimental, theoretical and numerical efforts were carried out to approach its value, which corresponds to the onset to the loss of flow symmetry and afterward of vortex shedding. Williamson [1] reviewed earlier studies and suggested a critical Reynolds number Re_c close to 49. Zdravkovich [2] indicated that when the Reynolds number is above 44, the wake starts shedding vortices into the stream and the vortex shedding begin to take place. Based on linear analysis, Barkley [3,4] found $Re_c \approx 46$. Resolving the biharmonic pure stream function form of the Navier–Stokes (N–S) equations using a finite difference scheme, Kalita and Sen [5] provide an estimation of Re_c in the interval $46.5 < Re_c \leqslant 47$. Sengupta et al. [6] conducted a detailed analysis of various results available in literature and concluded that Re_c may be numerical scheme and/or facility dependent. At the critical Reynolds number Re_c, the flow undergoes a Hopf bifurcation that leads to a two-dimensional oscillatory flow: the well-known von Karman vortex street [4]. In studying nonlinear instabilities for flow past a cylinder, Sengupta et al. [7] identified more than one Hopf bifurcation during flow instability and concluded that the reason for different experimental facilities and numerical methods reporting different Re_c is related to the receptivity of the flow field to background disturbances during the linear temporal growth of the disturbance field.

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At critical Reynolds number Re_c, the boundary layers separate alternately from each side of the cylinder surface and form two shear layers. Separation can either be laminar or turbulent according to the regime of the flow in the boundary layer. Since the innermost part of the shear layers, which is in contact with the cylinder, moves much more slowly than the outermost part, which is in contact with the free flow, the shear layers roll into the near wake, where they fold on each other and coalesce into discrete vortices [8]. It should be noted here that even if the oncoming flow is steady, the unsteadiness is intrinsically generated by friction on the cylinder wall and the von Kármán Street is formed downstream of the cylinder [9].

Physically, the onset of instability is almost instantaneously [10,11] and is caused by several kinds of perturbations. Braza et al. [12] identified the non-uniform inlet condition, the surface irregularities of the boundaries, and the vibrations in the system as perturbation sources. These physical destabilizing effects can hardly be considered in numerical simulations and are generally absent. However, due to the importance of the vortex shedding phenomenon, numerical simulations are in high demand and are widely used. Computational approaches solve the Navier–Stokes equations, produce the vortex shedding and are able to mimic the physical instabilities [13].

Numerically, the onset of instability is due to the amplification of the truncation and round-off errors, as well as errors due to the numerical scheme and the sweep direction in the solution procedure [13–16]. This is true even if the domain geometry and boundary conditions are perfectly symmetric [17,18]. Moreover, for any value of Reynolds number, the temporal evolution of the near wake is traced through its initial growth in size as a symmetrical twin vortex structure, followed by a transition to an asymmetrical twin vortex pattern before finally yielding to the onset of vortex shedding which only after some further time achieves regular periodic shedding [17]. However, for low Reynolds numbers, numerical simulations show that the flow always achieves a steady symmetric pattern after a long establishment period [12]. Nowadays, the onset of instability and the flow convergence to the periodic state still remains extremely slow, namely for low Reynolds numbers. Consequently, minimizing the transient time corresponding to the onset of the vortex pattern is of great challenge in the order to better approach the computational flow dynamics past a cylinder to real physics dynamics.

To trigger the onset of flow asymmetry and then minimize transient time, the method of the impulsive start from rest is often used. This method is formulated using steady state inviscid solution as initial condition for the viscous flow simulation [7,11,19–21]. Although there is no experimental evidence of a truly impulsive start [22], several authors use this technique to investigate the problem of vortex shedding, namely for low Reynolds number ([19] for Re = 40 and 100, [7] for Re = 60, 100 and 250). The flow may be impulsively started by oscillating ([5] for Re = 44, 46.5, 47 and 50) or rotating and/or by translating the cylinder ([23] for Re = 200). Besides the impulsive start technique, several authors disturb either the inlet boundary condition or the condition on the cylinder surface. Some of them chose to use the asymmetric perturbation of the inlet condition [14,17,24]. While others chose to perturb initially the inlet condition by adding small-amplitude random perturbation [17,25]. The perturbation can be introduced also on the cylinder condition by the presence of discrete roughness element [21], by rotation [12,26,27] or by small surface asymmetry [28–30].

Table 1 lists the main perturbation and excitation methods used to trigger the onset of flow asymmetry and vortex shedding. Although each of these artificial excitations break the symmetry of the flow, triggers the vortex shedding generation process and can quickly lead to periodic state, it is a source of energy to the system and may influence the modelling results. Therefore, to better approach the physical reality, an important condition is that the disturbance cannot be the source of energy sustaining the flow regime [14].

Since the numerical codes generated vortices by amplification of truncation and round-off errors, the adopted initial conditions for transient computation starts may affect the onset of the vortex shedding and, therefore, the time needed to reach the periodic state. However, to our knowledge, the idea of accelerating the appearance of numerical vortices by acting on initial conditions has never been published and that's what we propose to investigate in the present paper.

The main goal of this study is to examine and highlight the role that initial conditions play in the onset of vortex shedding. Knowing that the effects of initial conditions are limited in time and are quickly forgotten, the simulations results with and without initial conditions perturbation (i.e. with a uniform initial velocity field) should be similar. The main question that we try to answer is: what are the nature and the size of the ideal perturbation leading to the smallest time for the development of vortex shedding? In order to answer this question, a laminar flow of a viscous incompressible fluid past a circular cylinder is considered. Two-dimensional numerical simulations were carried out at low Reynolds numbers using a perturbed flow field as initial condition. The simulations are first conducted assuming a uniform initial velocity and this is considered later as a reference case for comparison. Next, we introduce an initial lateral streamwise gradient. The paper is structured as follows. Section 2 presents the physical problem. Section 3 briefly describes the numerical model. Section 4 summarizes the main results of two reference cases. Section 5 explains the suggested initial condition perturbation. Section 6 tests the damping of initial conditions' effects. Section 7 presents the main obtained results and discusses the pertinence of the suggested approach. Finally, conclusions and perspectives are presented in Section 8.

2. Physical model

We are interested in this study to the two-dimensional fluid flow around a circular cylinder obstacle in an infinite domain. The infinite nature of the domain is considered using both symmetry of the domain geometry and uniformity of boundary conditions. In this domain, the fluid moves with a uniform streamwise velocity (i.e. $u = U_\infty$ everywhere). Physically, this means that the cylinder is introduced into an infinite uniform free-stream flow. This case will be considered as a reference case to which the simulation results with different initial conditions will be compared.

3. Numerical method

3.1. Governing equations

In the present study, the flow features past a circular cylinder are modelled assuming a two-dimensional, unsteady, viscous and incompressible fluid flow with constant properties. The governing equations for mass and momentum conservation are expressed as follow

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

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