Computers and Fluids 147 (2017) 102–118

Contents lists available at ScienceDirect

Computers and Fluids

journal homepage: www.elsevier.com/locate/compfluid

Three dimensionality in the wake of the flow around a circular cylinder at Reynolds number 5000

D.E. Aljure, O. Lehmkhul, I. Rodríguez, A. Oliva*

Heat and Mass Transfer Technological Center (CTTC), Universitat Politècnica de Catalunya BarcelonaTech (UPC), ESEIAAT, Colom 11, 08222, Terrassa, Barcelona, Spain

ARTICLE INFO

Article history:
Received 31 March 2016
Revised 24 December 2016
Accepted 1 February 2017
Available online 2 February 2017

Keywords:
Direct numerical simulation
Coherent structures
Vortex shedding
Shear layer
Wake three-dimensionality
Vortex dislocations

ABSTRACT

The turbulent flow around a circular cylinder has been investigated at $Re = 5000$ using direct numerical simulations. Low frequency behavior, vortex undulation, vortex splitting, vortex dislocations and three dimensional flow within the wake were found to happen at this flow regime. In order to successfully capture the wake three dimensionality, different span-wise lengths were considered. It was found that a length $L_Z = 2\pi D$ was enough to capture this behavior, correctly predicting different aspects of the flow such as drag coefficient, Strouhal number and pressure and velocity distributions when compared to experimental values. Two instability mechanisms were found to coexist in the present case study: a global type instability originating in the shear layer, which shows a characteristic frequency, and a convective type instability that seems to be constantly present in the near wake. Characteristics of both types of instabilities are identified and discussed in detail. As suggested by Norberg, a resonance-type effect takes place in the vortex formation region, as the coexistence of both instability mechanisms result in distorted vortex tubes. However, vortex coherence is never lost within the wake.

1. Introduction

Aerodynamic research has been going on for over 100 years where bluff body flow has been a very active research area and the flow around a circular cylinder a benchmark problem. Flow over this geometry has been extensively studied and the understanding of the dynamics and structures present has grown extensively in the past few decades. Geometrical simplicity and an abundance of relevant three dimensional results make this an exceptional case study. Experimental observations on this geometrical configuration date back to the late XIX – early XX century with the work of famous physics like Strouhal, Von Kármán and Prandtl; and hundreds of research papers have been written concerning the study of the present configuration (see for instance Williamson [48] and citations therein).

The laminar to turbulent transition in the present case is limited by the particular geometry and flow conditions, i.e. transition is not induced by the body geometry itself but rather by the interactions of different unstable regions in the flow. Three different zones can be found: the boundary layer in the cylinder, two shear layers on top and bottom of the body and, finally, the wake. Extensive work carried out by different authors such as Bloor [2], Gerrard [8], Roshko [35], 36] have made possible the description of the different regimes encountered and the particular phenomena associated with them.

A number of experimental and numerical studies [49,29,39,40, amongst others] have been focused on the phenomenon of three-dimensional wake transition which occurs at Reynolds numbers between $Re = 190 - 260$ [48]. This regime has been associated with discontinuities in the Strouhal number and base pressure coefficient as the Reynolds number increases. Furthermore, the appearance of vortex pairs, vortex adhesion [49], upstream facing vortex loops [18] and low-frequency irregularities [2] have also been reported. This geometry and the three dimensional behavior present was further studied by Williamson [46], who observed an additional phenomenon: vortex dislocations. This phenomenon is related to the break down of turbulence and is considered as a mechanism of wake transition, as the vortex shedding shifts from wake mode A to wake mode B. Natural vortex dislocations have been also reported in different wake-type flows such as mixing layers [5], the flow over a flat plate [22], the flow over a cone [28] and the flow over a stepped cylinder [19]. Vortex dislocations might be seen as defects in the two dimensional vortex tubes whose continuity is broken as a consequence of the frequency difference between two span-wise cells [46] or between cells of

---

* Corresponding author.
E-mail addresses: davidal@cttc.upc.edu (D.E. Aljure), oriol.lehmkuhl@bsc.es (O. Lehmkhul), ivette.rodriguez@upc.edu (I. Rodríguez), oliva@cttc.upc.edu, cttc@cttc.upc.edu (A. Oliva).

http://dx.doi.org/10.1016/j.compfluid.2017.02.004
0045-7930/

similar frequency which are out-of-phase with each other [5]. Braza et al. [4] studied the natural vortex dislocation phenomenon that occurs in the three dimensional wake transition at $Re = 220$. They showed the existence of naturally occurring dislocations in the near wake, and the similarity of these structures to those obtained by Williamson [46] using a ring on the cylinder to force their appearance. Additionally, they analyzed the physical processes related to the introduction of stream and cross-stream-wise vorticity components and their impact on the span-wise variations of the Von Kármán vortex filaments and described the steps that lead to vortex dislocations.

At higher Reynolds numbers, vortex irregularities have been suggested to be related with fundamental changes in the three-dimensionality of the wake past a cylinder. Several authors have observed transitional behavior around $Re \approx 5000$. This behavior is evidenced by different changes in wake configuration. An increase in the fluctuations of drag and lift forces and a loss of coherence in the vortex shedding (observed as a wider bandwidth in the spectrum at the vortex shedding frequency) have been reported. Furthermore, several authors point to changes in the base pressure profile and the vortex formation length, as well as, variation in length and behavior of the shear layers.

Son and Hanratty [38] studied the velocity gradients around the cylinder observing an increase in the separation angle with Reynolds number. Additionally they found that a small zone of positive velocity gradient, which they named zone B, appeared after the separation point and could be explained by the existence of a small separation bubble that decreased in size with Reynolds number. Finally, observations for the region following region B, region C (back of the cylinder), showed that for $Re = 5000$ and $Re = 10,000$ the gradient in this zone remains small with a slight increase towards the cylinder centerline, larger for $Re =$10,000. For Reynolds numbers $Re \geq$ 20,000 the trend in the profile seemed to change with a much larger increasing rate as it approaches the cylinder center. The authors stated that results in this section are open to question due to the small magnitude of this quantity and that it may be changing direction. Kourta et al. [14] observed, through hot-wire measurements and flow visualizations, two different types of interaction between the vortex shedding and the small scale structures in the transition process in the cylinder wake. For a lower Reynolds range, that they defined as $2000 < Re < 16,000$, they found a strong interaction due to similar frequencies in both phenomena. For the larger Reynolds numbers, $16,000 < Re < 60,000$, the two phenomena are disconnected and the small vortices act as an eddy viscosity. Unal and Rockwell [43] found that the formation length decreased for Reynolds numbers $Re > 1900$, indicating an increase in the base pressure coefficient. Additionally for the higher Reynolds numbers they studied, $Re = 3400$ and $Re = 5040$, a distortion in the velocity fluctuation distribution with respect to the kinetic energy appeared, larger for $Re = 5040$. Finally, they performed an eigenfunction analysis on the velocity distribution along the shear layer and compared it with theoretical distributions finding that the data for Reynolds numbers between $1900 < Re < 3400$ follows the theory, however large deviations were observed for $Re = 5040$. Lin et al. [20] performed experimental observations on this geometry, observing for the Reynolds numbers $Re = 1000$ and $Re = 5000$ low levels of vorticity and low speed in the base region. They argued that the vortex formation is decoupled from the near-base region of the cylinder and this implied a predominant role of convective-type instabilities leading to large vortex formation. The authors wondered whether there is a shift in the vortex formation regime causing a change from the convective to a global instability mechanism for higher Re numbers and if this change in vortex formation mechanism is responsible for the large changes in the base pressure coefficient observed in the Reynolds number range $1000 < Re <$ 10,000.

Norberg, in several works [23,24,26,27], showed the appearance of a transition in wake behavior for the flow at $Re \approx 5000$ including undulating vortex filaments and vortex splitting. He suggested that these structures might be related to what he observed as a shift from high to low quality vortex shedding. Finally, Norberg suggested that for $Re < 5000$ transition to turbulence is triggered by vortices in the wake, whereas after that Re number turbulence is triggered by a Kelvin–Helmholtz (KH) instability within the shear layer. At the critical value ($Re = 5000$) the two mechanisms coincide causing a resonance like behavior. Prasad and Williamson [31] investigated the changes in the three-dimensional near-wake structures over the time for $190 < Re <$ 10,000 and the influence of the end conditions on the flow structure. The authors paid special attention to the wake transition regime and its relation with the flow parameters, including the vortex shedding frequency. They devoted especial attention to the flow around $Re \approx 5000$ where they stated the wake might be experiencing a fundamental change. They observed different phenomena such as a discontinuity in the value of the Strouhal number, a twin-peak spectrum near the vortex shedding frequency and vortex dislocations along the cylinder axis. The authors question whether these observations were introduced by the end plates used in their experiments, the finite length of the cylinder or if they were a real feature of the flow. Rajagopalan and Antonia [32] also studied the flow over a large range of Reynolds numbers in the sub critical range and focused on the shear layer instabilities. They found that the relation of the ratio between shear layer frequency and vortex shedding frequency with the Reynolds number changed around $Re = 5000$. This change supports the previous observations of a change in the flow organization at this Re number. Supporting the hypothesis proposed by Lin et al. [20], Rajagopalan and Antonia [32] suggested that a convective instability mechanism governs the flow for $Re > 5000$ rather than a global instability mechanism.

It is important to note that some scattering of results has been observed in this Reynolds number range, probably due to different experimental configurations (span-wise length, blocking ratio, time integration period, inflow conditions). However, the work done so far evidences the presence of a transition in wake behavior for the flow around $Re \approx 5000$. The present work aims to investigate this configuration using direct numerical simulations (DNS) in order to confirm the presence of the three dimensional behavior observed at $Re = 5000$ and to try to deepen the knowledge into the transitional behavior observed. Additionally, a detailed study into the instability mechanisms present in the flow is carried out. To the authors' knowledge no DNS studies have been performed at this Reynolds number.

2. Mathematical and numerical model

2.1. Governing equations and numerical method

In order to study the flow, the incompressible Navier–Stokes equations are solved:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} - \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \rho^{-1} \frac{\partial p}{\partial x_i} = 0 \tag{2}$$

where u_i is the three-dimensional velocity field (u_1, u_2, and u_3 are also referred to as U, V and W), p is the pressure field, ν stands for the kinematic viscosity and ρ for the density of the fluid.

A collocated unstructured mesh is built and the spatial discretization is carried out by means of finite volume techniques. A second-order conservative scheme [45] for the continuous differential operators, an explicit second order self-adaptive scheme