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Numerical study on coherent structure behind a circular disk

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ABSTRACT

A numerical study on the turbulent wake behind a circular disk of an aspect ratio 5 at $\text{Re}=10^4$ is performed. Three characteristic instabilities are confirmed, including a low-frequency instability at $\text{St}_L \approx 0.05$–0.06 due to pumping motion of the recirculation region, large-scale vortex shedding at $\text{St}_V \approx 0.14$, and the shear-layer instability at $\text{St}_{KH} \approx 1.4$–$1.6$. A large waviness of the wake coherent structures is observed and further studied with the definition of the wake positions. It is suggested that the coexistence of lots of irregular helical/helical-like modes in the wake leads to the waviness. The traces of the wake positions in phase diagram could give a good description of the irregular motion of the large-scale vortex shedding location, which occurs at the same large-scale vortex shedding frequency. Two preferred states in the wake are found, which could induce two asymmetric topologies. The reflectional-symmetry-breaking regime at laminar wake is persistent in the turbulent wake and gives rise to the two asymmetric flow states. And, it is found that the coherent structure from the conditional averaging of each preferred state bears a remarkable resemblance to the wake structure at RSB mode for a low Reynolds number. Considering the topology from the conditional averaging of each preferred state and the flow visualizations at RSB mode, a spatial coherent wake structure at $\text{Re}=10^4$ is then proposed.

1. Introduction

Flow behind a circular disk is widely studied due to its close relation to many aero- and hydrodynamic applications, such as car side view mirror, flame holder in industrial burners or gas turbine combustors. As a typical turbulent shear flow, it also helps in understanding many dynamical processes. However, the wakes of circular disks are much less studied compared with other basic geometries, i.e. spheres and cylinders (Kiya et al., 2001).

The disk wakes at low Reynolds numbers below 300 have been extensively studied recently. The wake of a circular disk is dependent on Reynolds number and the aspect ratio, which is defined as $\chi = d/w$, where d and w are the diameter and the thickness of the disk, respectively. The first bifurcation leading to a steady planar-symmetric state, was observed for all the investigated configurations, i.e. the flat disk ($\chi=\infty$) considered by Natarajan and Acrivos (1993), Fabre et al. (2008) and Meliga et al. (2009), and disks of aspect ratio larger than one considered by Fernades et al. (2007) ($\chi=2$–10), Shenoy and Kleinstreuer (2008) ($\chi=10$), Auguste et al. (2010) ($\chi=3$) and Szaltys et al. (2011) ($\chi=6$). The critical Reynolds number for the first bifurcation was found to be between 115 and 117 for the flat disk. The second bifurcation was found to be a three-dimensional state with hairpin vortex periodically shedding for a flat disk and a thin disk of aspect ratio $\chi=10$. The second bifurcation Reynolds number was in the range 121–125.6 for the flat disk, and 155 for a thin disk of aspect ratio $\chi=10$.

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The influence of the disk aspect ratio on the critical Reynolds numbers for the first two bifurcations was studied by Fernades et al. (2007). It was found that the aspect ratio was related to the critical Reynolds numbers by functions of $Re_{c1} \approx 116.5(1+\chi^{-1})$ and $Re_{c2} \approx 125.6(1+\chi^{-1})$. Since the second bifurcation broke the planar-symmetry to form a three-dimensional wake, this state was called reflectional-symmetry breaking (RSB) mode by Fabre et al. (2008). A third bifurcation leading to a periodic state with the planar-symmetry recovering was observed for a flat disk and the thin disk of aspect ratio $\chi=10$. The critical Reynolds number was found at $Re_{c3} \approx 140$ (Fabre et al., 2008) and 143 (Meliga et al., 2009) for the flat disk, and at $Re_{c3} \approx 172$ for the thin disk ($\chi=10$) (Shenoy and Kleinstreuer, 2008). The forth bifurcation was found to lead to a periodic three-dimensional flow with irregular rotation of the separation region for a thin disk ($\chi=10$). A low frequency close to one third of the 'leading frequency' of the previous regimes was detected in this state. The critical Reynolds number was found at $Re_{c4} \approx 280$. Recently, an extensive parametric study dealing with oblate spheroids and flat cylinders in the range $\chi \in [1,\infty]$, $Re \in [100,300]$ was carried out by Chrust et al. (2010). It basically confirmed the bifurcation scenarios summarized above and delimited the domain of existence of each state in the (χ, Re) plane. More detailed results for wake bifurcations of fixed bodies at the low Reynolds numbers can refer to a review of Ern et al. (2012).

The influence of the aspect ratio on the dynamics in the wake of a circular disk at low Reynolds numbers has also been investigated recently. Shenoy and Kleinstreuer (2010) studied the effect of the aspect ratio on the vortex shedding behavior of fixed, and freely moving circular disk. Disks with aspect ratio of $\chi=2$ and 4 were selected, and periodic vortex shedding was observed at $Re=240$ for both fixed and freely moving disks. The aspect ratio significantly changes the structure of the vortices shed from the disk. For the fixed disk of $\chi=2$, periodic shedding of one-sided hairpin vortex loops was observed, while periodic shedding of hairpin vortex loops was observed from the diametrically opposite location of the disk for the fixed disk of $\chi=4$. However, the non-dimensional vortex shedding frequencies in the two cases are the same, i.e. 0.122. More recently, the influence of the aspect ratio on the value of onset instability, the evolution of perturbation and the obtained vorticity bifurcation branches of the instability in the wake of a circular disk were experimentally investigated by Bobinski et al. (2014). Different disks with aspect ratio $\chi=1$–24 were investigated in the range of Reynolds number from 0 to 500. It was found that the initial non-dimensional vortex shedding frequency for each disk, remained close to 0.15. The investigations seem to show that the non-dimensional vortex shedding frequency is less influenced by the aspect ratio.

As the Reynolds number increases, the wake of a circular disk becomes more complex due to the transition from laminar to turbulent flow. The turbulent wakes behind a circular disk at high Reynolds numbers were less studied. Most experimental works have been focused on the observations of the wake structures, vortex shedding mechanism and instabilities in the wake. Fuchs et al. (1979), Roberts (1973), Cannon et al. (1993) and Berger et al. (1990) examined the flow structures in the disk wakes at Reynolds number of 10^4–10^5 using cross-spectral analysis. An anti-symmetric and highly coherent structure was observed, which was dominated by helical modes $m=\pm 1$ at a frequency $St_V=0.135$, with the helical structures rotating around the axis of the wake. Higuchi et al. (1996) confirmed the primary helical mode at a Reynolds number of 10^4 in the disk wake by flow visualization. Lee and Bearman (1992) conducted an experimental investigation of the wake structure behind a circular disk using a conditional sampling technique. By analyzing the velocity signals obtained by two hot-wire probes set at different circumferential positions, the vortex structure was differentiated into positive and negative modes which respectively corresponded to phase lead and phase lag between the velocity signals measured at the two azimuthal locations. They summarized from their experimental findings that the wake behind a circular disk consisted of lots of irregular vortex loops. Perry and Watmuff (1981) made another attempt of using the phase-averaged technique to study the vortical structures in the three-dimensional turbulent wakes. They observed that the large-scale vortical structure retained their identity for long streamwise distance and contributed significantly to the Reynolds stress. As a comparison, for the sphere wake, visual observations have shown that vortex structures form a double helix (Pao and Kao, 1977) or hairpin loops (Achenbac, 1974; Sakamoto and Haniu, 1990) at Reynolds number of $\sim 10^3$, and the sphere wake becomes completely turbulent with quasi-periodically spaced vortex loops or rings at Reynolds number of $\sim 10^4$ and beyond (Taneda, 1978). The wake structures are yet to be fully understood despite of these previous experimental studies.

The vortex shedding mechanism also attracted some investigators' attention. Fuchs et al. (1979) found that vortex shedding from an axisymmetric body was random in phase circumferentially, but with an anti-phase characteristic for vortex shedding at azimuthal locations of 180° apart. This result was supported by Berger et al. (1990), who found that the helical structures in the wake existed in fragments and randomly twisted in either a clockwise or anti-clockwise manner. Miau et al. (1997) performed experiments for individual realizations of the vortex shedding process behind a circular disk at Reynolds numbers of 10^3–10^5, and showed that the randomness of phase differences involved in the vortex shedding process was essential to satisfy the axisymmetric property of the global flow. It seemed that previous studies showed an agreement on the randomness of the vortex shedding location azimuthally. However, no clear description of the randomness has been given.

As for the instabilities in the turbulent wake, Berger et al. (1990) stated that the disk wake was dominated by three instabilities: axisymmetric pulsation of the recirculation bubble at a low frequency $St_L \approx 0.05$, anti-symmetric fluctuations induced by a helical vortex at a natural frequency $St_V \approx 0.135$, and a high frequency ($St_{KH} \approx 1.6$) instability of the separated shear layer. The three characteristic instabilities were also found for the turbulent sphere wake (Rodriguez et al., 2011). Because of very few studies on this topic, the characteristic instabilities in the turbulent wake of a disk need to be confirmed by more investigations.

Few studies have been reported about the influence of the aspect ratio on the dynamics at turbulent disk wakes. However, it is noted that for the Re from 10^4 to 10^5, the value of the non-dimensional vortex shedding frequency is very close to a constant 0.135 despite the difference of aspect ratio ($\chi=13.3$; 10, 14.3) (Berger et al., 1990; Miau et al., 1997).

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