NUMERICAL STUDY OF A VORTEX RING IMPACTING ON A CIRCULAR CYLINDER

Heng Ren, Xiyun Lu[a)]
Department of Modern Mechanics, University of Science and Technology of China, Hefei, Anhui 230026, China

Summary The interaction of a vortex ring with a circular cylinder at $Re = 3000$ in three dimensions is investigated using large eddy simulation (LES). We investigate the evolution of the vortex structure and find three typical evolution processes of the secondary vortex. Firstly, a secondary vortex is formed and its part moves inward to the primary vortex ring. Secondly, two loop-like vortices are formed and move in opposite directions. Finally, the two vortices collide and lead to small-scale vortex structures.

INTRODUCTION

A vortex located close to a solid body generates a boundary layer along the body surface that is subject to a favorable pressure gradient on one side of the vortex and an adverse pressure gradient on the other side. Boundary-layer separation in the adverse pressure gradient region leads to an ejection of secondary vorticity generated on the surface into the surrounding fluid. The secondary vorticity interacts with the primary vortex and can lead to such consequences as vortex rebound from the surface or breakup of the vortex into small-scale turbulence.

While there have been a considerable number of studies on impacts of a vortex ring on a flat wall (Walker *et al.* 1987; Chu, Wang & Chang 1993; Orlandi & Verzicco1993; Chu, Wang & Chang 1995; Cheng & Luo 2010; Lauren & Paul 2011) and columnar vortex on a circular cylinder (Gossler & Marshall 2001), little has been done for interaction between a vortex ring and a circular cylinder in three dimensions. The only work, to our knowledge, is an experimental study by Naitoh *et al.* (1995), who observed transition of flow field from laminar to turbulent regime when the ratio of cylinder diameter to core diameter Π increased from 0.25 to 0.38.

In this work, we will investigate the three-dimensional flow structures of a vortex ring impacting on a circular cylinder with different vortex ring radius at $Re = 3000$, corresponding to $\Pi = 5$ and 10 in Naitoh's experiment. The present paper is concerned with dynamics of the secondary vortex induced by the primary vortex ring.

NUMERICAL METHOD AND COMPUTATIONAL OVERVIEW

Large eddy simulation is implemented in the present study with dynamic subgrid scale models. The governing equations are numerically solved by a finite-volume method. The temporal integration is performed using an implicit approximate-factorization method with sub-iterations to ensure the second-order accuracy. Both the convective and diffusive terms are discretized with the second-order centered schemes, and a fourth-order low artificial numerical dissipation is employed to prevent numerical oscillations. The present numerical strategy has already been applied with success to a wide range of turbulent flows such as compressible flows past an aerofoil (Chen *et al.* 2010) and over a wavy cylinder (Xu *et al.* 2010). We have carefully examined the physical model and numerical approach used in this study and have verified that the calculated results are reliable.

A vortex ring of radius R is initially placed at a distance $z = 3R$ from the axis of the cylinder at $z = 0$. The initial vorticity distribution of the vortex ring is assigned by a Gaussian function (Orlandi & Verzicco 1993).

In the computation, we use five girds and three time steps to assess the effects of gird resolution and time step. We find the gird $533 \times 351 \times 481$ and time step $\Delta t = 0.001$ can accurately capture the dynamics of the secondary vortex and interaction between primary vortex ring and secondary vortex. The present computational domain is divided into 96 sub-domains for parallel processing.

RESULTS AND DISCUSSION

Figure 1 shows the three-dimensional vortex structures depicted by the iso-surface of the Q-criterion. Radius of the vortex ring is $R = 1$. Firstly, due to the adverse pressure gradient generated by the primary vortex ring on the cylinder surface and local vorticity concentration within the boundary layer, a secondary vortex separates and lifts up from the surface of cylinder, then part of the secondary vortex structure around $y = 0$ plane is convected inwards to the primary vortex and interacts with the cylinder surface, as shown in figure 1(*a*). The formation and movement of the secondary vortex at the first stage is similar to vortex ring impacting on a flat wall. At the secondary stage, the secondary vortex starts to wrap around the primary vortex ring and forms two loop-like vortices on both sides of the cylinder. Then the two vortices begin to move in opposite direction, as shown in figures 1(*b*) and 1(*c*). Finally, the two vortices come into collision with each other and the interaction between them leads to complex three-dimensional topological vortex structure and the transition of flow from laminar to turbulence, as shown in figures 1(*d*) and 1(*f*).

When the radius of the vortex ring is $R = 2$, three-dimensional vortex structure is shown in figure 2. We observe the strength of the secondary loop-like vortices is higher and the vortex structure is more obvious with the increase of the vortex ring radius, as shown in figure 2(*b*). In the process of secondary vortices moving in opposite direction before

[a)] Corresponding author. Email: xlu@ustc.edu.cn.

they collide with each other, the loop-like secondary vortex structure breaks down into multiple small-scale vortices, this is the main difference between figure 1 and figure 2, as shown in figures 2(*d*) and 2(*g*).

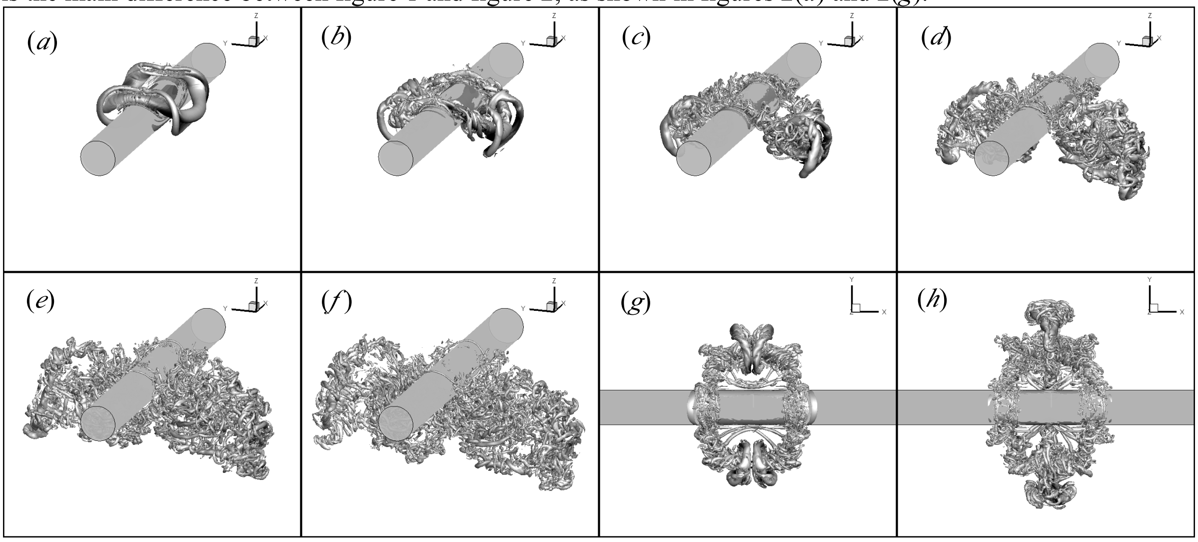

Figure 1. Vortex structure evolution at $R = 1$, the iso-surface of vorticity $Q = 2.0$. (*a*) $t = 15.0$, (*b*) $t = 17.5$, (*c*) $t = 20.0$,(*d*) $t = 22.5$, (*e*) $t = 25.0$, (*f*) $t = 27.5$. (*g*) and (*h*) are top view of figures 1(*c*) and 1(*d*) respectively.

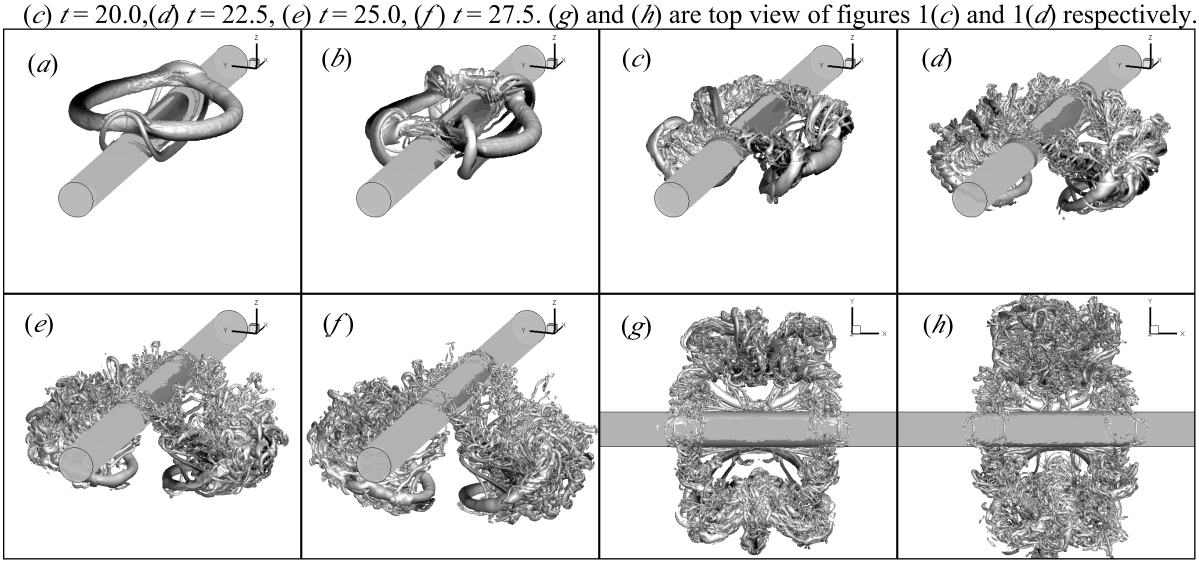

Figure 2. Vortex structure evolution at $R = 2$, the iso-surface of vorticity $Q = 2.0$. (*a*) $t = 15.0$, (*b*) $t = 17.5$, (*c*) $t = 20.0$, (*d*) $t = 22.5$, (*e*) $t = 25.0$, (*f*) $t = 27.5$. (*g*) and (*h*) are top view of figures 2(*e*) and 2(*f*) respectively

CONCLUSIONS

We have numerically studied a vortex ring impacting on circular cylinders with different radius at *Re*=3000. We present the effects of vortex ring radius on the evolution of the vortex structure and find the evolution of the secondary vortex structure can be divided into three different stages. Firstly, the secondary vortex separates and lifts up from the surface of cylinder, then part of the secondary vortex structure around $y = 0$ plane is convected inwards to the primary vortex and interacts with the cylinder surface. Secondly, the secondary vortex starts to wrap around the primary vortex ring and forms two loop-like vortices on both sides of the cylinder. Then the two vortices begin to move in opposite direction. Finally, the two vortices come into collision with each other and complex three-dimensional topological vortex structure is formed.

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