Large eddy simulation of an oblique vortex ring impinging on a flat wall

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***Abstract*— The oblique interaction of a vortex ring with a flat wall at $\mathrm{Re}=4\times10^4$ in three dimensions is investigated using large eddy simulation (LES). We consider the effect of initial located angle of a vortex ring. For small angle case, the secondary vortex ring is generated from the wall and then moves toward and interacts with the wall. While for big angle case, the strength of the secondary ring is strong and large deformation occurs for it. The dominant mode for both primary and secondary vortex rings is n=11. In the late stage of interaction, the strong vortex-vortex and vortex-wall interactions lead to the large vortex structures breakdown into small scale vortices and the flow transfers to turbulence. The fully turbulent flow is marked by the same order of magnitude of perturbation energy for low modes.**

***Index Terms*— Vortex ring, flat wall, large eddy simulation, oblique collision.**

[1] INTRODUCTION

The interaction of vortical structures with solid boundaries is a fundamental fluid dynamic topic which has received considerable attention in recent years. The interest in this subject is partly due to several practical applications, (e.g. impact of helicopter rotor vortices with following rotor blades or with the vehicle airframe, chopping of a pump intake vortex by the turbine blades, and interaction of an aircraft trailing vortex with a following aircraft or with the airstrip during landing and take-off), and partially in order to gain a better insight in the fundamental dynamics of vorticity in such flow situations. As one of the simplest and important forms of vortex motion, vortex rings widely exist in nature. The interaction of vortex rings with solid boundaries is an important problem in fluid dynamics. This subject is also associated with a variety of practical applications, such as vortex rings extinguishing gas and oil well fires [1], cavitated rings used for underwater drilling [2], and modeling the interaction between the downburst and the aircraft [3]. Moreover, the underlying flow phenomena and physical mechanisms are still unclear and are of great interest for detailed studies.

Vortex rings interacting with a flat wall has been extensively studied. These studies [4-9] showed that as the primary vortex ring moves gradually toward the wall, its rate of approach slows and its radius continues to increase; meanwhile, considerable secondary vorticity is generated on the surface. When the Reynolds number, based on the initial diameter and translational speed of the vortex ring, is larger than about 500, the secondary vorticity separates from the surface and interacts with the primary vortex ring resulting in the ring rebounding from the wall. Actually, these studies are mainly limited to relatively low Reynolds numbers, the highest Reynolds number in these studies is about 2840 [9]. The experimental study [9] has revealed that, beyond *Re* = 3000 for the interaction between a vortex ring and a flat wall, the primary vortex ring will no longer remain stable as it approaches the wall.

For the oblique collision of a vortex ring with a wall, to our knowledge, only in the numerical studies by Olandi et al. [6]. In this letter, we investigate the effect of initial angle on the vortical structures when a vortex ring impings with a fla wall.

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[2] NUMERICAL METHOD

To investigate a vortex ring impinging on a flat wall, the three-dimensional Favre-filtered compressible Navier-Stokes equations in generalized coordinates are employed. The equation of state for an ideal gas is used and the molecular viscosity is assumed to obey the Sutherland law. To non-dimensionalize the governing equations, the radius of the initial vortex ring and the far-field variables are used as characteristic quantities. It should be indicated that, similar to LES on the evolution of longitudinal stationary vortices [10], the present simulation is for a low Mach number of 0.3 based on the far-field speed of sound, which is very near the incompressible limit. Sreedhdar and Ragab [10] have verified that the approach based on the compressible N-S equations can reliably predict the incompressible flow characteristics of the vortex evolution.

The large eddy simulation is implemented for turbulence closure. In order to model some terms in the Favre-filtered equations arising from the unresolved scales, dynamic subgrid-scale (SGS) models for turbulent flows are employed. A detailed description of the mathematical formulation of the governing equations and the SGS models have been given in our previous paper [11-12].

The governing equations are numerically solved by a finite-volume method. As employed in our previous work [11-12], the convective terms are discretized by a second-order central scheme and the viscous terms by a fourth-order centered scheme. Time advancement is performed by an implicit approximate factorization method with sub iterations to ensure a second-order accuracy. Moreover, the present numerical methods have already been used successfully to a variety of turbulent flows and have been verified to provide the reliable calculations.

[3] COMPUTATION MODEL AND BOUNDARY CONDITIONS

As illustrated in Fig. 1, a vortex ring of radius R_0 is initially placed at $\boldsymbol{x_c} = (0, 0, H)$, H is the distance between the vortex ring center and the wall, α is the angle between the vortex ring and the wall.

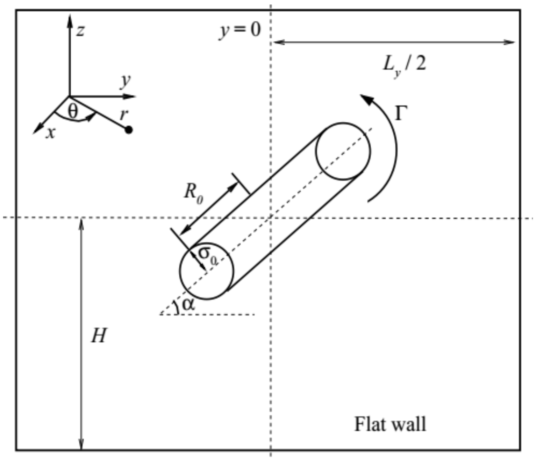

Fig. 1. Schematic diagram of a vortex ring approaching a flat wall.

The initial vorticity distribution of the vortex ring is assigned by a Gaussian function. The initial translational speed of the vortex ring can be represented as

$$u_v = \frac{\Gamma}{4\pi R_0}(\ln\frac{8R_0}{\sigma_0} - \frac{1}{4}), \quad (1)$$

where σ_0 is the initial core radius and Γ is the circulation of the vortex ring. To deal with the instability of the vortex ring, an azimuthal disturbance with an amplitude of 2×10^{-4} is introduced by imposing a radial displacement on the axis of the ring.

In the computation, we calculate two cases with $\alpha = 10^\circ$ and 30° respectively. For both cases, slenderness ratio of the vortex ring is $\sigma_0 / R_0 = 0.4$ and the initial translational speed of the ring is $u_s = 0.3$. Reynolds number based on the translational speed and ring diameter is $Re = 4 \times 10^4$, and the corresponding Reynolds number based on circulation of the vortex ring is $Re_\Gamma = 9.15 \times 10^4$.

The computational domain extends for 16 ring radii in the x and y directions and 12 radii in the vertical direction, with $L_x/R_0 = L_y/R_0 = 16$, $L_z/R_0 = 12$. Based on our careful examinations, a mesh of size $N_x \times N_y \times N_z = 641 \times 641 \times 263$ with resolution $R_0 = 40\Delta x$ is used in the computation, where N_x and N_y are dimensions of the mesh in two horizontal directions x and y, and and N_z is the dimension in the vertical direction z. The grid-spacing is uniform in x and y, and grid stretching is employed in z to increase the grid resolutions near the surface. In the transversal x and y directions, periodicity boundary conditions are used. In the vertical z direction, the flow is bounded by a no-slip wall on the bump surface and far-field boundary condition at $z = L_z$.

We will validate our code by a comparison with the existing results for a vortex ring impacting a flat wall at $Re = 830$. For the vortex ring/wall interacting case, the initial conditions are the same with experiment by Chu *et al*. [8]. The Gaussian ring is initially placed at the vertical position $H = 3R_0$ and we use the grid resolution $R_0 = 30\Delta x$ for the simulation which is same with the cases in Cheng *et al*. [4]. We compare the trajectory of the primary vortex ring center with the experiment and the numerical study, as shown in Fig. 2. Clearly, our results are convergent to the experimental data and better than numerical results by Cheng *et al*. using Lattice Boltzmann method.

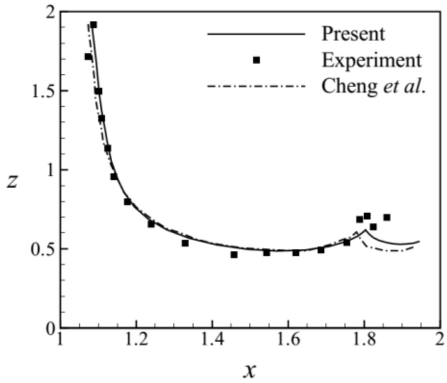

Fig. 2. The trajectory of the primary ring center for $Re = 830$. The solid and dashdot lines present the numerical results obtained in this work and by Cheng *et al*. respectively. The symbol represents the experimental data.

[4] RESULTS AND DISCUSSION

At high Reynolds number, the collision of vortex ring and wall leads to the complex flow structures. Figure 4 shows the evolution of three-dimensional vortex structures depicted by isosurface of the Q-criterion for $\alpha=10^\circ$ case. A sequence of events takes place when a vortex ring approaches a flat wall. Firstly, when the vortex ring is close to the wall, the ring entrains surrounding fluids and a thin boundary layer is generated on the surface. As the ring moves closer to the wall, it begins to stretch and the induced boundary layer grows rapidly. At t=22.5, the left part of vortex ring interacts with the wall and the boundary layer undergoes separation in the adverse pressure gradient region leading to ejection of vorticity generated on the surface into the surrounding fluid. At t=25, we observe a oblique second vortex ring is generated. For the second votex ring, the vorticiy of left part is stronger than the right part. After the second vortex ring is generated, it lifts up from the wall and then interacts with the primary ring. The interaction between the primary and secondary rings decelerates the radial expansion of the primary ring and causes the primary ring to rebound from the wall. At t=27.5, we observe the secondary vortex ring is moving far away from the wall and it develops into a wavy structure, which is mainly due to the growth of azimuthal instability. Then the secondary ring moves inwards. At t=30, the left part of sencond ring begins to collide with the wall. The complex interaction between secondary vortex ring, wall and primary vortex ring leads to the complex vortical structures in the flow. It is seen the hair-pin vortices are generated at t=32.5. After t=35, the strong vortex-vortex and vortex-wall interactions lead to breakdown of vortex structures into small-scale vortices and complex three-dimensional topological structures appear.

For $\alpha=30^\circ$ case, the left part of second vortex ring is generated at t=25. Due to its strong vorticity, the left part interacting with the priamry ring leads to the deformation of the second ring, as shown in figure 4(c). After the right part of second ring is generated, it moves far away from the wall. The right part of secondary ring moves above the primary vortex ring at t=32.5 and we observe a large number of vortices wrapping around the primary and secondary rings respectively t=35. While for α=10° case, the strength of the secondary ring is weak and the large deformation does not occur for it. This is the main difference between the two cases. After t=37.5, the strong vortex-vortex and vortex-wall interactions lead to breakdown of vortex structures into small-scale vortices and complex three-dimensional topological structures appear.

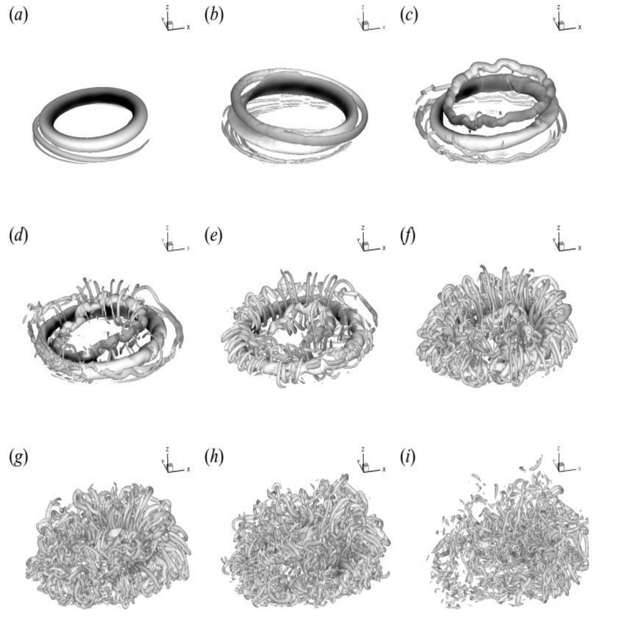

Fig. 3. Evolution of vortex structures for the case α=10° shown by isosurface of the Q-criterion (*Q*=2). (a) t=22.5, (b) 25.0, (c) 27.5, (d) 30.0, (e) 32.5, (f) 35.0, (g) 37.5, (h) 40.0, (i) 45.0.

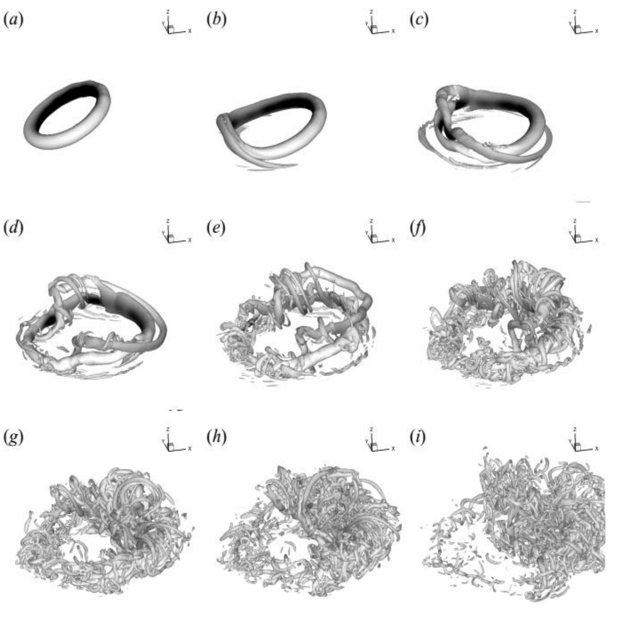

Fig. 4. Evolution of vortex structures for the case α=30° shown by isosurface of the Q-criterion (*Q*=2). (a) t=22.5, (b) 25.0, (c) 27.5, (d) 30.0, (e) 32.5, (f) 35.0, (g) 37.5, (h) 40.0, (i) 45.0.

[5] CONCLUSION

The interaction between a vortex ring and a flat plate has been studied by means of the large eddy simulation technique. The vortical flow phenomena and the underlying physical mechanisms were investigated and are summarized briefly as follows.

We investigate the effect of initial angle of a vortex ring on the dynamics of vortex structures. For α=10° case, the secondary ring moves far away from the wall and then moves toward the wall. The interaction between the vortices and the wall are similar to the vertical collision of vortex rings and flat wall. While for α=30° case, large deformation and breakdown of secondary vortex ring occurs. This is mainly due to the stronger vorticity and higher growth rate of perturbation in secondary ring . The dominant mode for both primary and secondary rings is n = 11 and is consistent with the previous results.

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