Commun. Comput. Phys.
doi: 10.4208/cicp.150115.210715s

Vol. **18**, No. 4, pp. 1122-1146
October 2015

Dynamics and Instability of a Vortex Ring Impinging on a Wall

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Received 15 January 2015; Accepted (in revised version) 21 July 2015

Abstract. Dynamics and instability of a vortex ring impinging on a wall were investigated by means of large eddy simulation for two vortex core thicknesses corresponding to thin and thick vortex rings. Various fundamental mechanisms dictating the flow behaviors, such as evolution of vortical structures, formation of vortices wrapping around vortex rings, instability and breakdown of vortex rings, and transition from laminar to turbulent state, have been studied systematically. The evolution of vortical structures is elucidated and the formation of the loop-like and hair-pin vortices wrapping around the vortex rings (called briefly wrapping vortices) is clarified. Analysis of the enstrophy of wrapping vortices and turbulent kinetic energy (TKE) in flow field indicates that the formation and evolution of wrapping vortices are closely associated with the flow transition to turbulent state. It is found that the temporal development of wrapping vortices and the growth rate of axial flow generated around the circumference of the core region for the thin ring are faster than those for the thick ring. The azimuthal instabilities of primary and secondary vortex rings are analyzed and the development of modal energies is investigated to reveal the flow transition to turbulent state. The modal energy decay follows a characteristic $-5/3$ power law, indicating that the vortical flow has become turbulence. Moreover, it is identified that the TKE with a major contribution of the azimuthal component is mainly distributed in the core region of vortex rings. The results obtained in this study provide physical insight of the mechanisms relevant to the vortical flow evolution from laminar to turbulent state.

AMS subject classifications: 76F65, 76D17, 76F06

Key words: Large eddy simulation, vortex ring, vortical structure, instability, turbulent state.

1 Introduction

Vortex rings widely exist in nature and engineering and can be considered as one typical vortex motion [1]. The interaction of vortex ring with a solid wall has also received

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considerable attention as discussed below for extensive work. When the Reynolds number (*Re*) based on the translational speed and initial diameter of the vortex ring is high enough, the interaction can lead to the breakdown of vortex rings and transition to turbulent state [2–4]. Thus, various fundamental mechanisms dictating the relevant flow behaviors are still completely unclear, in particular for the high-Reynolds-number vortical flow, and are of great interest for further detailed studies.

Vortex ring interacting with a flat wall has been studied numerically and experimentally [2, 5–12]. As the primary vortex ring evolves toward the wall, its approach rate slows and its radius increases gradually in accompany with the generation of secondary vorticity on the wall. When the Reynolds number is larger than about 500 [9,11], the secondary vortex separates from the surface and interacts with the primary vortex ring resulting in the ring rebounding from the wall. Actually, these studies described above are mainly limited to relatively low-Reynolds-number flow regime and the highest Reynolds number in these studies is about 2840 [2]. The experimental study has revealed that the primary vortex ring no longer remains stable as it approaches the wall at high Reynolds number [2]. Thus, the instability of vortex rings and transition to turbulence need to be investigated for a vortex ring impinging on a wall in the high-Reynolds-number regime.

The evolution of a free vortex ring is a prototypical vortical flow relevant to some fundamental behaviors, such as growth, instability, breakdown and transition of vortex ring. Extensive investigations have been carried out theoretically [13–16], experimentally [17–23], and numerically [24–27]. Krutzsch [13] first studied the instability of vortex ring and found that the vortex ring becomes unstable with some stationary waves distributed around its azimuthal direction. Crow [14] investigated the aircraft trailing vortices and presented the development process of the vortex instability. Then Maxworthy [17–19] and Widnall [20] verified experimentally that the stationary azimuthal waves grow in the surface at 45° relative to the propagation direction of vortex ring, and the wave number depends on the slenderness ratio of core radius to ring radius. Widnall and Tsai [16] gave the theoretical explanation of the instability and indicated that a straining field in the neighbourhood of the vortex core leads to the amplification of small perturbation. Shariff et al. [25] established a viscous correction to the growth rate in terms of their direct numerical simulation (DNS) results. Dazin et al. [21,22] experimentally investigated the linear and nonlinear stages of vortex ring decay and found that the straining field causes the instability. Bergdorf et al. [26] numerically studied the evolution of vortex rings at $Re_\Gamma = 7500$ based on the circulation of the vortex ring and demonstrated the formation of a series of hair-pin vortices during the early turbulent stage. Archer et al. [27] further investigated the effects of Reynolds number and core thicknesses on the vortex ring evolution from laminar to the early turbulent regime and indicated that the onset of the turbulent state is associated with the formation of a series of hairpin vortices.

Compared with the studies of the instability of free vortex rings, the investigation relevant to the instability of a vortex ring impinging on a wall is still scarce. Walker et al. [2] experimentally investigated the trajectories of vortical structures for $564 \leq Re \leq 2840$. At