Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **6**, No. 3, pp. 261-280

DOI: 10.4208/aamm.2013.m285
June 2014

Large Eddy Simulation of a Vortex Ring Impacting a Bump

Heng Ren[1], Ning Zhao[2] and Xi-Yun Lu[1,*]

[1] *Department of Modern Mechanics, University of Science and Technology of China, Hefei 230026, Anhui, China*
[2] *Department of Aerodynamics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, Jiangsu, China*

Received 10 July 2013; Accepted (in revised version) 27 September 2013

Available online 17 April 2014

Abstract. A vortex ring impacting a three-dimensional bump is studied using large eddy simulation for a Reynolds number $\mathrm{Re}=4\times 10^4$ based on the initial diameter and translational speed of the vortex ring. The effects of bump height and vortex core thickness for thin and thick vortex rings on the vortical flow phenomena and the underlying physical mechanisms are investigated. Based on the analysis of the evolution of vortical structures, two typical kinds of vortical structures, i.e., the wrapping vortices and the hair-pin vortices, are identified and play an important role in the flow state evolution. The boundary vorticity flux is analyzed to reveal the mechanism of the vorticity generation on the bump surface. The circulation of the primary vortex ring reasonably elucidates some typical phases of flow evolution. Further, the analysis of turbulent kinetic energy reveals the transition from laminar to turbulent state. The results obtained in this study provide physical insight into the understanding of the mechanisms relevant to the flow evolution and the flow transition to turbulent state.

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

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

1 Introduction

As one of the typical forms of vortex motion, vortex rings widely exist in nature and engineering. The interaction of vortex rings with solid or fluid boundaries is a fundamental problem in fluid dynamics and has received considerable attention. This subject is also

*Corresponding author.
URL: http://staff.ustc.edu.cn/∼xlu/
Email: renheng@mail.ustc.edu.cn (H. Ren), zhaoam@nuaa.edu.cn (N. Zhao), xlu@ustc.edu.cn (X. Y. Lu)

associated with a variety of practical applications, such as cavitated rings used for underwater drilling [1] and the downburst and aircraft interaction [2]. Moreover, the relevant physical flow behaviors and mechanisms are still unclear and are deserved to be studied.

Vortex ring interacting with a flat wall has been extensively studied [3–16]. These studies showed that as the primary vortex ring moves gradually toward the wall, its rate of approach slows down and its radius continues to increase. Meanwhile, the primary ring induces considerable secondary vorticity on the wall. When the Reynolds number of the ring is larger than 500 based on the initial diameter and translational speed of the vortex ring, the formation of the secondary ring occurs and then it interacts with the primary vortex ring. Actually, these studies are mainly restricted to relatively low Reynolds numbers, the highest Reynolds number in these studies is about 2840 [5]. Experimental study [5] has revealed that, beyond $\mathrm{Re}=3000$, the primary vortex ring will no longer remain stable as it approaches the wall. Thus, the instability and transition to turbulence for the vortex ring evolution should be considered when the Reynolds number becomes large enough.

Comparing with the numerous studies of vortex ring interacting with a flat wall, the investigation relevant to a vortex ring impacting a curved surface is scarce. Orlandi [17] numerically studied vortex pairs interacting with a two-dimensional circular cylinder with free-slip and no-slip boundary conditions. For the free-slip case, the dipole is observed to split into two vortices and then to rejoin on the cylinder. While for the no-slip interaction, the generation of dipolar and tripolar structures occurs on the cylinder surface. Verzicco et al. [18] further studied this problem. They found that the induced vortices become more apparent as the diameter of the cylinder increases. Allen et al. [19] presented experimental results of a vortex ring impinging on a moving sphere. They found that the secondary vorticity generated on the sphere surface leads to a decrease of the fluid impulse and an acceleration of the sphere. Recently, Sousa [20] studied a vortex ring impacting a stationary sphere for $\mathrm{Re}=1000$ using direct numerical simulation (DNS). After the secondary vortex ring is formed, they found its interaction with the primary ring results in the fast decay of circulation for the secondary ring.

For the vortex evolution with its transition to turbulence at large Reynolds number, large eddy simulation (LES) is a useful tool to study the flow behaviors from laminar to turbulent regime. Sreedhar and Ragab [21] used LES to investigate the response of longitudinal stationary vortices subjected to random perturbations and the subsequent transition to turbulence. The Reynolds number based on the core radius and maximum initial tangential velocity is 10^5. Mansfield et al. [22] employed Lagrangian LES to investigate the collision of two coaxial vortex rings and successfully captured several distinctive phenomena observed experimentally [23]. Faddy and Pullin [24] numerically studied the flow structures of two counter-rotating vortices in three dimensions. They performed the simulations using DNS at low Reynolds number 10^3 and LES at high Reynolds number 2×10^4, where the Reynolds number is based on the circulation of the Lamb-Oseen vortex.

In this paper, an LES technique is utilized to investigate the effects of bump height and vortex core thickness on the dynamics of vortical structures and the turbulent behaviors