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DNS of Acoustic Sound Generated by Collision of Vortex Rings

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ABSTRACT

Interactions of two vortex rings may be one of the most fundamental mechanisms of sound generation in three-dimensional vortical flows, and have been studied for a head-on collision [1, 2] as well as an oblique collision [3]. In recent years, direct numerical simulation (DNS) became a realistic tool in the field of computational aeroacoustics with the rapid growth in computational power. Inoue *et al.* [2] investigated, by using axisymmetric DNS, the sound generation in an axisymmetric flow field produced by head-on collision of two coaxial vortex rings. They successfully captured the generation and propagation processes of the sound pressure waves. However, the detailed processes of the sound generation in the three-dimensional vortical flows, such as vortex reconnection, have not been clarified completely yet. Our purpose in this study is, by using three-dimensional DNS, to investigate the vortex sound radiated from the oblique/head-on collision of two vortex rings for several collision angles, and to increase our understanding of the mechanisms of sound generation and propagation in the three-dimensional vortical flows.

The three-dimensional, unsteady, compressible Navier-Stokes equations are solved by a finite difference method. An eighth-order-accurate compact Padé scheme [4] is used for spatial derivatives, together with the forth-order-accurate Runge-Kutta scheme for time integration. Non-reflecting boundary conditions are adopted at outer boundaries. A non-uniform rectangular grid system is applied. The reliability of the grid system has been examined by a number of refinement tests. We consider the collision of two vortex rings with equal strength. The two vortex rings are set initially to move along the paths intersecting at an angle $2\theta_c$, which we call the collision angle. The vortex rings are assumed to have a Gaussian distribution of vorticity initially. The ratio of the core radius to the ring radius is fixed to be 0.3. The Reynolds number based on the initial translational velocity of the vortex rings and the ring radius is fixed to be $Re{=}500$, and the Mach number of the initial translational velocity is $M_0{=}0.15$. In this study, the collision angles are prescribed to be $2\theta_c{=}\pi$ (head-on collision), $7\pi/8$, $3\pi/4$, $5\pi/8$, and $\pi/2$ (oblique collision at a right angle).

In order to confirm the reliability of our numerical results, we have compared the sound pressure generated by the head-on collision obtained by the present DNS with that obtained by the axisymmetric DNS of Inoue *et al.* [2], and showed that the two results are in a good agreement. For the oblique collision at a right angle, comparison has also been made between the acoustic modes obtained by the present

DNS and those by the experiment of Kambe *et al.* [3]. Although both the Mach number and Reynolds number are different, the two results showed a good qualitative agreement.

We have examined the effects of the collision angle on both the near-vortical field and the far-acoustic field. As for the near vortical-field, typical examples of vortex ring collision are presented in terms of iso-vorticity surface for the case of $2\theta_c{=}\pi/2$, in Fig. 1. As seen from the figure, the two vortex rings approach at their respective self-induced velocities, and collide with each other. Then, the vortex rings stretch and their radii increase as time increases. In the case of the head-on collision ($2\theta_c{=}\pi$), the vorticity field (as well as the pressure field) is always axisymmetric, and the collision occurs at the same time over the entire circumference of the rings. On the other hand, for the cases of oblique collision, the upper parts of the vortex rings collide earlier than the lower parts, and the core radii of the upper parts become slender more rapidly than those of the lower parts. For the oblique collision at a right angle ($2\theta_c{=}\pi/2$), the first reconnection occurs; the two vortex rings reconnect to form a single distorted ring. The reconnection of vortex lines becomes more significant as collision angle decreases. Shown in Fig. 2 is the instantaneous pressure distribution on the collision plane ((x, z) planes), including the far-field, for the case of $2\theta_c{=}\pi/2$. The figure shows that the sound pressure waves, generated by the vortex collision (Fig. 1), propagate radially from the near-vortical region to the far-field. The pressure wave having sufficiently large amplitude is generated twice in any of the cases. The differences in the directivities of wave propagation have been examined by decomposition of the far-field sound pressure. As a result, we found that, the quadrupolar nature is predominant in any of the cases. In the first quadrupole mode, qualitative differences are seen among the cases, indicating that the sound pressure waves propagating toward the upper and lower sides are significantly affected by the collision angle. For a smaller collision angle, the second pulse becomes to have asymmetric features exhibited by the first octupole mode.

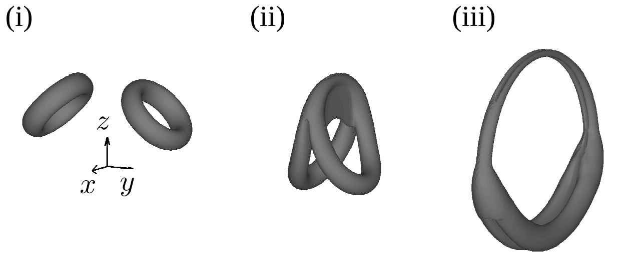

Figure 1: Perspective views of iso-surfaces of the vorticity. $|\boldsymbol{\omega}|{=}0.6$. $2\theta_c{=}\pi/2$. (i) $t{=}40$, (ii) $t{=}60$, (iii) $t{=}80$.

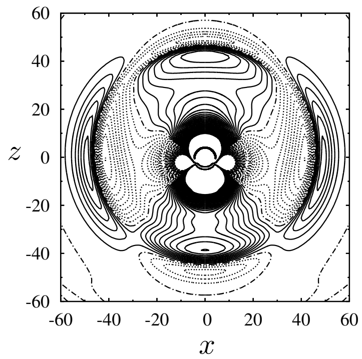

Figure 2: Pressure distribution on the (x, z) plane, at $t{=}100$. $2\theta_c{=}\pi/2$. ———, $\Delta p{>}0$; $-\cdot-\cdot-$, $\Delta p{=}0$; $\cdots\cdots\cdot$, $\Delta p{<}0$.

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