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Numerical Simulations of Two Coaxial Vortex Rings Head-on Collision

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Abstract. Vortex rings have been a subject of interest in vortex dynamics due to a plethora of physical phenomena revealed by their motions and interactions within a boundary. The present paper is devoted to physics of a head-on collision of two vortex rings in three dimensional space, simulated with a second order finite volume scheme and compressible. The scheme combines non-iterative approximate Riemann-solver and piecewise-parabolic reconstruction used in inviscid flux evaluation procedure. The computational results of vortex ring collisions capture several distinctive phenomena. In the early stages of the simulation, the rings propagate under their own self-induced motion. As the rings approach each other, their radii increase, followed by stretching and merging during the collision. Later, the two rings have merged into a single doughnut-shaped structure. This structure continues to extend in the radial direction, leaving a web of particles around the centers. At a later time, the formation of ringlets propagate radially away from the center of collision, and then the effects of instability involved leads to a reconnection in which small-scale ringlets are generated. In addition, it is shown that the scheme captures several experimentally observed features of the ring collisions, including a turbulent breakdown into small-scale structures and the generation of small-scale radially propagating vortex rings, due to the modification of the vorticity distribution, as a result of the entrainment of background vorticity and helicity by the vortex core, and their subsequent interaction.

AMS subject classifications: 65M10, 78A48

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1 Introduction

This article includes research into the regularities of formation and motion of one of the most interesting types of liquid and gas vortex motions–vortex ring. It is well known that a vortex ring deforms as it collides in an obstacle. A recent experiment devoted to a head-on collision of two vortex rings in three dimensional space [1] shows that the deformation of the rings is not so easy to study and predict. A question has been raised as how the collision would affect the motion of a vortex rings and the vorticity distribution. The present article is an attempt to address this issue. For the reader's convenience, this article is separated in four sections, each presenting a specific topic, each part containing a few sections.

The vortex flow is one of the fundamental types of fluid and gas motion. It is characterized by the localization of vorticity in bounded regions of a space, beyond which the vorticity is absent or rapidly falls to zero. Concentrated vortices are often observed in nature, exemplified through atmospheric cyclones, whirlwinds and tornados, oceanic vortices, whirlpools on a water surface, and ring vortices caused by explosive out burs of volcanoes. In technical devices, concentrated vortices are formed when the flow is separated from sharp edges of flying vehicles and ships, airplane wings, etc. One remarkable and frequent type of concentrated vortices is a vortex ring which constitutes of a vortex tube closed into a toroidal ring, moving in a surrounding fluid. It appears like an isolated body which is out of contact with solid boundaries of the flow region, if such boundaries exist. The formation and motion of vortex rings are an important part of the dynamics of a continuum medium and have been studied for more than a century. These investigations promoted elucidation of many general mechanisms of vortex motions, and recently provided a basis for developing high efficiency operating procedures [2].

Originally, vortex rings sparked interest because of simplicity of their generation and observation, and due to approximately steady characteristic of fluid motion relative to the vortex ring. Systematic scientific studies of vortex rings have been performed by many famous researchers in mechanics and physics, e.g., Helmholtz (1858); Kelvin (1867); Reynolds (1876); Thomson and Newall (1885); Prandtl and Tietjens (1934); Joukowski (1937); Lamb (1932); Prandtl (1949); Taylor (1953); Sommerfeld (1950); Feynman (1964); Kirchhoff (1962); Batchelor (1967). Their investigations resulted in the development of mathematical models for vortex rings in the framework of an ideal (inviscid) fluid, and formulas were obtained for determination of the fundamental vortex ring properties: impulse, energy, translational velocity, and streamline structure. For a long time the concepts of vortex rings were based only on these theoretical results.

Vortex rings have fascinated researchers for a long time because of their frequent appearance in nature and technology, as well as the way they can be easily produced experimentally. They are mainly generated by exhaustion of a finite-length submerged jet from a circular orifice or from an open end of a cylindrical tube. Using this technique, it is easy to determine and control the condition of vortex ring formation. Here the problem of obtaining accurate analytical estimations of the properties of the vortex ring being