Simulation and analysis of the evolution of a single vortex ring using a state-of-the-art vortex method

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Abstract

The evolution of a single vortex ring has been the subject of numerous investigations within scientific literature as a remarkable stability of the vortex ring is observed even at highly dynamical flow regimes. The stability of the vortex ring allows a very effective transport of momentum in the fluid – a property which is observed to be both harmful and helpful in different aspects of nature. Whereas the formation of vortex rings in blood vessels significantly increases the risk of aneurysms to rupture, many creatures depend on vortex rings as an efficient method of obtaining propulsion and flight.

By studying the topology of the flow field of a vortex ring has extended the general knowledge of how instabilities causes a flow to transition from a laminar to a turbulent state. Although extensive, much of the analysis of the previous investigations of vortex rings has been focused on the topology of the vortex core structure and the time history of different moments of the flow field. Only little effort has been put into analysing the local deformation of vorticity through the velocity gradient tensor governing the flow deformation.

The enstrophy density can be viewed as a quantity for the local rotational kinetic energy of the fluid and thus represents the coupling between the vorticity (rotation rate) and the kinetic energy of a fluid particle. As the vorticity field is deformed into sheet- and tube-like structures, the conservation of angular momentum causes an energy transfer between different length scales of the flow characterised by the change in enstrophy density. Hence the alignment of the vorticity vector with the principal axis of the flow deformation constitutes an essential quantity regarding the turbulent energy transfer and thus influences the "life expectancy" of the flow structures.

In this work we present the results of a single vortex ring simulation using a high order particle-mesh based vortex method with free-space boundary conditions (see Fig. 1). We present a detailed analysis flow field which is shown to exhibit different probable configurations of fluid deformation and vorticity alignment for each of the different "life stages" of the vortex ring.

Figure 1: Volume rendering of the vorticity magnitude at six different stages during the topological break-down of a vortex ring.