Gravity currents

The release of denser fluid into a lighter environment in the presence of a wall or a density interface develops into a gravity current. Gravity currents are widely found in engineering and environmental applications and are characterized by sharp density interfaces that develop strong Kelvin-Helmholtz vortices. Being able to track and visualize these vortices plays a very important role in understanding and describing the dynamics of the flow. The currents present a front, a body, and a tail (see figure 1(a)). The front manifests as a discontinuity in density that penetrates into the lighter fluid. For large Reynolds number flows, the sharp interface between heavy and light fluids rolls up into strong Kelvin-Helmholtz vortices as a consequence of baroclinic production of vorticity. These vortices move upstream into the body of the current where they undergo a complex dynamics, governed mainly by vortex stretching, and eventually decay to smaller scale turbulence (Cantero et al. 2007a). Some evidence of these processes can be seen in figure 1(b), which presents a planar gravity current front from a laboratory experiment. The channel-size Kelvin-Helmholtz vortices are populated by smaller scale vortices (Cantero et al. 2007b). The figure also shows the lobes and clefts that form at the leading edge of the current. Similar dynamics is found in cylindrical gravity currents. Figure 1(c) shows a 90° circular sector of a cylindrical density current from direct numerical simulation (Cantero et al. 2007a). The flow is visualized by an isosurface of the density field. Figure 1(c) shows three mature Kelvin-Helmholtz rings at the interface between the heavy and light fluids. The figure also shows the incipient formation of lobes and clefts in the lower region of the front.

Vortex Visualization in Gravity Currents

Gravity currents

The release of denser fluid into a lighter environment in the presence of a wall or a density interface develops into a gravity current. Gravity currents are widely found in engineering and environmental applications and are characterized by sharp density interfaces that develop strong Kelvin-Helmholtz vortices. Being able to track and visualize these vortices plays a very important role in understanding and describing the dynamics of the flow. The currents present a front, a body, and a tail (see figure 1(a)). The front manifests as a discontinuity in density that penetrates into the lighter fluid. For large Reynolds number flows, the sharp interface between heavy and light fluids rolls up into strong Kelvin-Helmholtz vortices as a consequence of baroclinic production of vorticity. These vortices move upstream into the body of the current where they undergo a complex dynamics, governed mainly by vortex stretching, and eventually decay to smaller scale turbulence (Cantero et al. 2007a). Some evidence of these processes can be seen in figure 1(b), which presents a planar gravity current front from a laboratory experiment. The channel-size Kelvin-Helmholtz vortices are populated by smaller scale vortices (Cantero et al. 2007b). The figure also shows the lobes and clefts that form at the leading edge of the current. Similar dynamics is found in cylindrical gravity currents. Figure 1(c) shows a 90° circular sector of a cylindrical density current from direct numerical simulation (Cantero et al. 2007a). The flow is visualized by an isosurface of the density field. Figure 1(c) shows three mature Kelvin-Helmholtz rings at the interface between the heavy and light fluids. The figure also shows the incipient formation of lobes and clefts in the lower region of the front.

Vortex identification by the swirling strength

The swirling strength criterion was introduced by Zhou et al. (1999) and extended later by Chakraborty et al. (2005). The basic idea of this criterion is to decompose the flow in the main directions of motion given by the vectors \( x \), \( y \), and \( z \). Here, \( x \) is the real eigenvector of the velocity gradient, \( \nabla \mathbf{u} \), with corresponding eigenvalue \( \lambda_{cr} \) and \( \mathbf{u} \), \( \mathbf{v} \), \( \mathbf{w} \), and \( \mathbf{r} \), are the conjugate pair of complex eigenvalues of \( \nabla \mathbf{u} \) with corresponding complex eigenvalues \( \lambda_{ci1}, \lambda_{ci2}, \lambda_{ci3} \). It can be shown (Chakraborty et al. 2005) that the flow undergoes spiraling motion on the plane spanned by \( \mathbf{v} \) and \( \mathbf{w} \) and stretching along the direction of \( \mathbf{r} \). The imaginary component of the complex eigenvalue pair, \( \lambda_{ci} \), is called the swirling strength and quantifies the local spiraling motion of the flow. By using the swirling strength, vortices are visualized by isosurfaces of \( \lambda_{ci}^2 \) equal to some threshold.

In this work, vortices are visualized by volumetric rendering of the absolute value of the swirling strength field, which allows for a more comprehensive visualization of the vortical structures (see figure 2).

Vortex dynamics

Figure 2 shows the vortical structures in the currents as visualized by volumetric rendering of the swirling strength computed from direct numerical simulations. The figure shows the time evolution of the currents for the early stages of development during which the Kelvin-Helmholtz rolls form and start to decay. Frames on the left in figure 2 correspond to a planar gravity current and frames on the right correspond to a cylindrical current. The first instance shown for the cylindrical current, \( t = 3.75 \), corresponds to the same instance of figure 1(c). At this time, three Kelvin-Helmholtz vortices have formed at the interface between heavy and light fluids and are marked V1, V2 and V3. The flow is visualized by an isosurface of the density field. Figure 1(c) shows three mature Kelvin-Helmholtz rings at the interface between the heavy and light fluids. The figure also shows the incipient formation of lobes and clefts in the lower region of the front.

Figure 3 shows the time evolution of the currents for the early stages of development during which the Kelvin-Helmholtz rolls form and start to decay. Frames on the left in figure 2 correspond to a planar gravity current and frames on the right correspond to a cylindrical current. The first instance shown for the cylindrical current, \( t = 3.75 \), corresponds to the same instance of figure 1(c). At this time, three Kelvin-Helmholtz vortices have formed at the interface between heavy and light fluids and are marked V1, V2 and V3. The flow is visualized by an isosurface of the density field. Figure 1(c) shows three mature Kelvin-Helmholtz rings at the interface between the heavy and light fluids. The figure also shows the incipient formation of lobes and clefts in the lower region of the front.

Vortex identification by the swirling strength

The swirling strength criterion was introduced by Zhou et al. (1999) and extended later by Chakraborty et al. (2005). The basic idea of this criterion is to decompose the flow in the main directions of motion given by the vectors \( x \), \( y \), and \( z \). Here, \( x \) is the real eigenvector of the velocity gradient, \( \nabla \mathbf{u} \), with corresponding eigenvalue \( \lambda_{cr} \) and \( \mathbf{u} \), \( \mathbf{v} \), \( \mathbf{w} \), and \( \mathbf{r} \), are the conjugate pair of complex eigenvalues of \( \nabla \mathbf{u} \) with corresponding complex eigenvalues \( \lambda_{ci1}, \lambda_{ci2}, \lambda_{ci3} \). It can be shown (Chakraborty et al. 2005) that the flow undergoes spiraling motion on the plane spanned by \( \mathbf{v} \) and \( \mathbf{w} \) and stretching along the direction of \( \mathbf{r} \). The imaginary component of the complex eigenvalue pair, \( \lambda_{ci} \), is called the swirling strength and quantifies the local spiraling motion of the flow. By using the swirling strength, vortices are visualized by isosurfaces of \( \lambda_{ci}^2 \) equal to some threshold.

In this work, vortices are visualized by volumetric rendering of the absolute value of the swirling strength field, which allows for a more comprehensive visualization of the vortical structures (see figure 2).

Vortex dynamics

Figure 2 shows the vortical structures in the currents as visualized by volumetric rendering of the swirling strength computed from direct numerical simulations. The figure shows the time evolution of the currents for the early stages of development during which the Kelvin-Helmholtz rolls form and start to decay. Frames on the left in figure 2 correspond to a planar gravity current and frames on the right correspond to a cylindrical current. The first instance shown for the cylindrical current, \( t = 3.75 \), corresponds to the same instance of figure 1(c). At this time, three Kelvin-Helmholtz vortices have formed at the interface between heavy and light fluids and are marked V1, V2 and V3. The flow is visualized by an isosurface of the density field. Figure 1(c) shows three mature Kelvin-Helmholtz rings at the interface between the heavy and light fluids. The figure also shows the incipient formation of lobes and clefts in the lower region of the front.

Acknowledgements

The simulations were performed at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign. Blake Harvey prepared figure 3.

References