Selective Visualization of Vortices in Hydrodynamic Flows

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Abstract

Vortices are important features in many research and engineering fields. Visualization is an important step in gaining more understanding and control of vortices. Vortex detection criteria fall into two categories: local scalar quantities, calculated at single points, and regional geometric / kinematic criteria, calculated for e.g. streamlines. The first category is easy to compute, but does not work in all cases. The second category is more intuitive and should work in all cases, but is more difficult to compute. We try to link the two categories with our selective visualization techniques [10]. By first selecting candidate areas based on the sclar quantities, the way is paved for applying a geometric criterion. Some early applications of this approach to hydrodynamic flows are shown.

1 Introduction

Vortices are important features in many types of flow research, and they are studied for theoretical and practical purposes. In fundamental flow research, the evolution of vortices is of great importance. In engineering applications, such as machinery design and hydraulics, vortices can either be desirable or undesirable, and designs are optimized to prevent or to promote the occurrence of vortices. Visualization of vortices is therefore important for understanding the underlying physics, and also for simulating and modifying designs. Previous applications of vortex detection and visualization have been described in oceanography [11], aerodynamics [5], and turbomachinery design [9].

Informally, a vortex is defined as a swirling flow pattern which will often behave as a coherent structure in time-dependent flows. A formal definition of a vortex cannot be easily given. Although in fluid dynamics research, several criteria have been developed for their detection, the essential characteristics are hard to formalize, and none of the existing criteria is entirely satisfactory.

The criteria can be roughly classified in two groups: local and regional criteria. We will briefly characterize these criteria, and propose a pragmatic approach toward vortex detection and visualization, which may combine the virtues of the two types of criteria, as shown in Figure 1. This approach uses the local criteria with our selection techniques [10], combined with regional criteria based on geometric properties of the flow field. We will show initial results of applications of this approach in hydrodynamics.

2 Approach

The first category of detection criteria is local and point-based, and consists of scalar quantities that can be determined at each point in a flow field. They are based on assumptions about the characteristics of the flow patterns in an (infinitely) small zone around a point. Examples of this type are pressure, vorticity, and various quantities derived from the velocity gradient $\nabla \mathbf{v}$. Concise surveys have been given by Banks and Singer [1] and Roth and Peikert [9]. All of these criteria are formal, and can be applied to points where the required quantities can be calculated. However, they may sometimes fail to detect obvious vortices, or

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find non-vortical structures. A reason for this may be that the point samples underlying the criteria do not always translate into regional characteristics.

The second category of criteria is regional and set-based, and tries to build upon the intuitive idea of a swirling pattern around a central set of points [7]. The criteria are based on geometric or kinematic flow characteristics, as represented by the shape of instantaneous streamlines. Robinson's vortex definition [8] is: "a vortex exists when instantaneous streamlines mapped onto a plane normal to the vortex core exhibit a roughly circular or spiral pattern, when viewed from a frame of reference moving with the center of the vortex core". Looking at Figure 2a, the vortices are immediately obvious, but more formal criteria are needed, which can be derived from differential geometry.
Two possible geometric criteria are:

• (Quasi-)closed streamlines [7]: these can be recognized by determining if the winding angle of a streamline has reached 2π, and the current point lies near the initial point. The winding angle of a (projected) streamline is the cumulative change of direction of the curve starting from a given point, with respect to a given external point.

• Accumulation of curvature centers [2]: the center of curvature of a streamline, or of its osculating circle, is determined at any given point in a field. If the centers of curvature for several sample points in a region lie closely together, this may indicate a vortex core. If there is no vortex, the centers will be randomly scattered in space.

These criteria are intuitively appealing, but they are still far from perfect. For instance, closed streamlines are not easy to find, as the number of streamlines is infinite. The curvature center technique turns out to be sensitive to 'noise': curvature centers are scattered, and smeared out when streamlines are not perfectly circular.

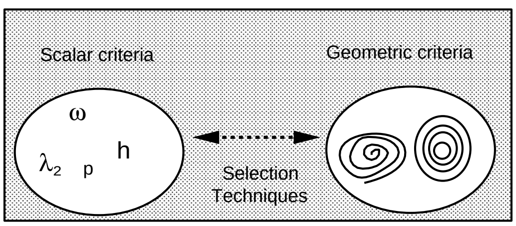


Figure 1: Local scalar criteria, and regional geometric criteria for detecting vortices

Therefore, we have used regional criteria in combination with the local techniques, by using our selection technique [10] as illustrated in Figure 1. This approach allows us to perform a pre-selection of candidate regions using local detection techniques, and then compute curvature centers or generate possibly circular streamlines within the selected regions. The Boolean combination (and / or) of local criteria used for the initial region selection may be very tolerant, as incorrectly detected vortices can then be discarded after using the regional geometric criterion.

3 Applications and Results

We have applied techniques from both categories to a number of hydrodynamic data sets resulting from simulations of the Bay of Gdańsk, the Pacific Ocean, and a transitional pipe flow.

From the first category of (scalar) detection criteria, we have chosen the λ_2 criterion, which is defined as the the second largest eigenvalue of the tensor $S^2 + \Omega^2$, with S and Ω being the symmetric and anti-symmetric components of the velocity gradient tensor $\nabla\mathbf{v}$. Regions of negative λ_2 are considered vortical regions [4].

For the second category of (geometric) detection criteria, we have extended De Leeuw's idea of interactive vortex finding to a more automated method. By sampling all grid points and computing the corresponding curvature centers, a new scalar field D (density) can be generated from the densities of the curvature centers. High densities of curvature centers in vortical regions will yield high scalar values, while sparse centers in other regions will give low values.

Bay of Gdańsk

The first application is a simulation performed at WL | Delft Hydraulics of the Bay of Gdańsk, a coastal area in Poland. The goal of the simulation was to investigate the flow patterns induced by tidal motion, the inflow of the Vistula river, and turbulence [6].

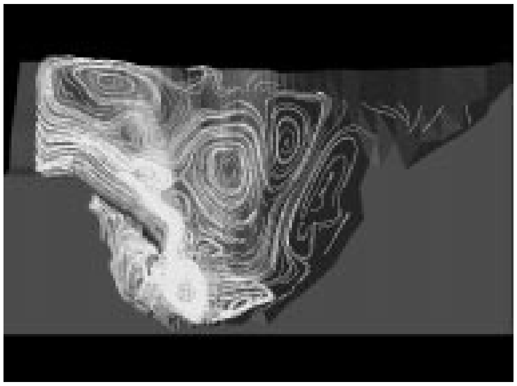
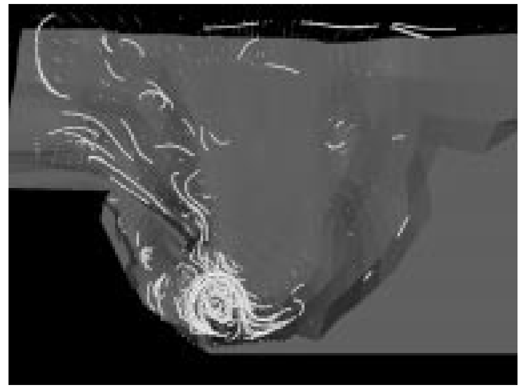
(a)  (b) 

Figure 2: The Bay of Gdańsk with (a) global streamlines and (b) selected streamlines where $\lambda_2 < -0.01$

To extract the rotating structures in Figure 2a, which are so obvious to the human observer, we apply our combined approach. First, we apply the scalar criterion $\lambda_2 < -0.01$ to detect candidate regions which might contain vortices. We use the selection techiques to find those regions and draw streamlines in them. This results in Figure 2b, which shows the selected grid points rendered as dots, and streamlines.

It can be seen that some of the regions of negative λ_2 capture actual vortices, while others do not. Due to the limited scope of the local, point-based criteria, some streamlines drawn have a locally very negative value of λ_2, but are not circular. Furthermore, this criterion finds the strong vortices, i.e. those with the highest velocity, but not the weak vortices.

Pacific Ocean

The next application is a data set as calculated in a numerical simulation of the surface layer of the Pacific Ocean [3]. The simulation employs the US Navy layered ocean model, a tool used by the Naval Oceanographic and Atmospheric Research Laboratory to assist in ocean prediction. Figure 3 (see Color Plate) shows the flow pattern using streamlines released from every grid point, colored with velocity magnitude.

To detect vortices, we apply a geometric detection criterion. Then, the selection technique is used to find regions where the density of curvature centers is relatively high: $D > 0.8D_{max}$. Figure 3 also shows the scalar field D rendered as a height field, including only those peaks that satisfy the above selection criterion. The selection technique is also used to draw streamlines confined to the selected regions.

Figure 4 (see Color Plate) shows these streamlines, and again scalar field D, which now has been colored with its magnitude, to enhance its contrast with the white streamlines. It can be seen that this technique finds most of the perfectly circular vortices, but not the more elongated vortices.

Transitional Pipe Flow

The last application is a direct numerical simulation (DNS) of transitional pipe flow, performed at the *Laboratory for Aero- and Hydrodynamics* at Delft University of Technology. Serving as a tool to explore the laminar-turbulent transition in pipe flow, the DNS tracks the spatial evolution of some local disturbance introduced from a wall area near the inflow. A prominent feature of this flow are the streamwise vortex pairs, whose origin, evolution and breakdown play an important role in the final transition to turbulent flow.

To visualize the results, several techniques are used. For a first indication of the vortical regions, isosurfaces are drawn for highly negative λ_2-values. Then desired points are marked, clustered and filtered by the use of selective techniques. This is an advantage of the selective techniques compared to a simple isosurface. Finally, streamlines are integrated from these clusters as candidates for a geometric criterion.

Figures 5 and 6 show a projected front view and a side view of the pipe flow (near the inflow), with green isosurfaces of $\lambda_2 = -8$, white cross marks for the selected points, and streamlines through the clusters of size ≥ 4. Figure 6 also shows a color slice with λ_2 mapped onto it, where red is the most negative value, green is zero, and blue the most positive.

It can be seen that the streamwise vortex pairs mentioned above, are successfully captured, especially in the projected front view. The visualization techniques here have proven a very helpful tool to reveal the true physics behind these visual clues.

4 Conclusions and Future Work

We have combined two categories of vortex extraction criteria: scalar and geometric. The scalar criteria reveal vortical structures with varying degrees of success, none of them is perfect. Stronger vortices with high angular velocity are usually found. Weaker vortices with slow rotation speed, which are quite common in hydrodynamics, often remain undetected by most local techniques.

The geometric criteria look promising because of the strong underlying theory, but at present we only have early implementations. We expect that in the future, improved implementations could perform better than the scalar methods.

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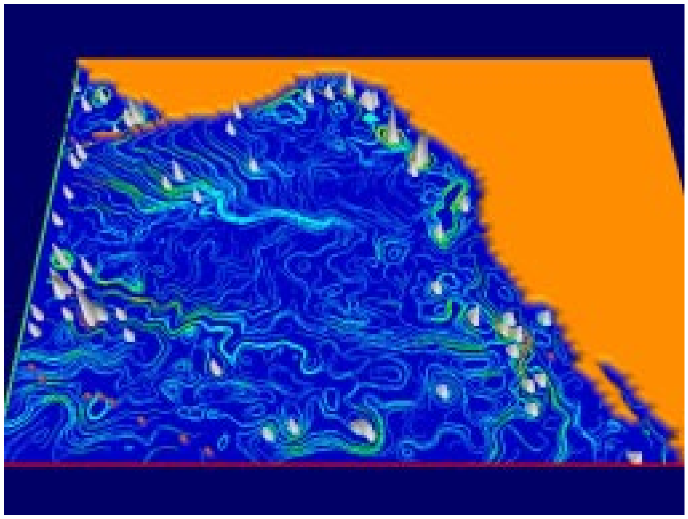

Figure 3: Pacific Ocean with global streamlines and height field of curvature center density $D > 0.8D_{max}$

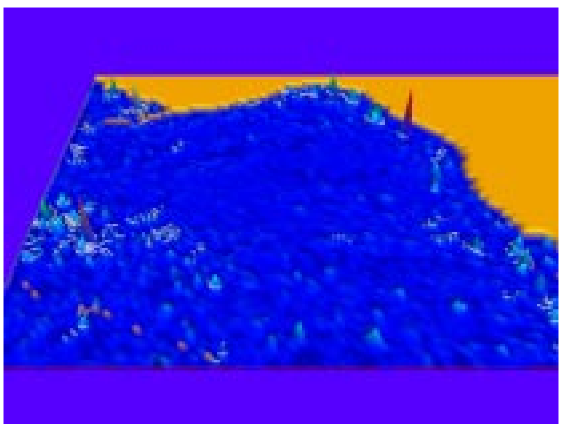

Figure 4: Pacific Ocean with streamlines from selected points

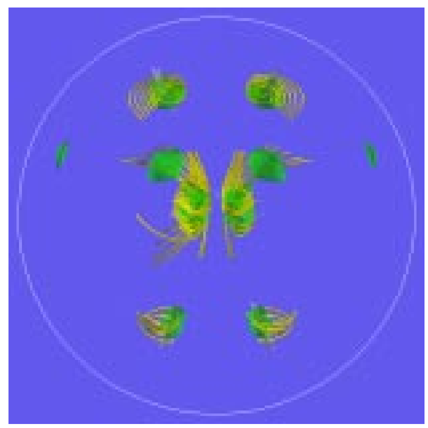

Figure 5: Transitional pipe flow (front view) with isosurfaces, selected clusters, and streamlines

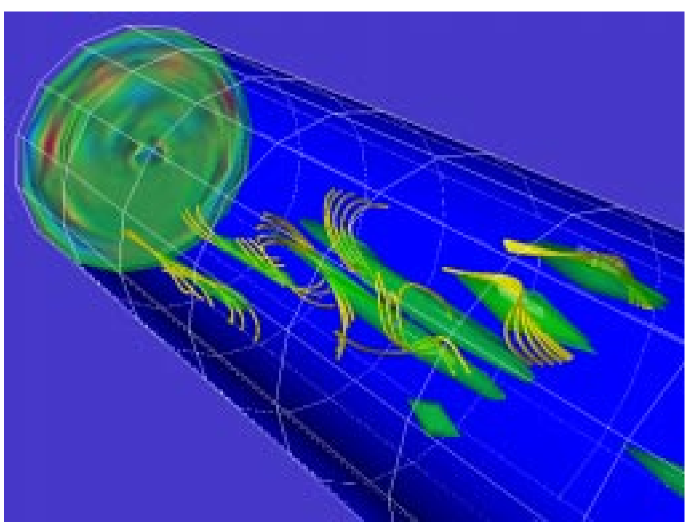

Figure 6: Transitional pipe flow (side view) with isosurfaces of $\lambda_2 = -8$, selected clusters, and streamlines through the clusters