Geometric Flow Visualization Techniques for CFD Simulation Data

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Abstract

Visualization of CFD simulation data on adaptive resolution, three-dimensional grids poses several challenges. The wide range of real-world data set sizes and the geometric versatility within individual, CFD simulation models present challenges to the engineers analyzing simulation results. Users also face perceptual problems such as occlusion, visual complexity, lack of directional cues, and lack of depth cues. We present a collection of geometric flow visualization techniques that address these challenges including oriented streamlines, streamlets, and a streamrunner tool. Two novel approaches are included: a real-time animated streamline technique and streamcomets. We place special emphasis on necessary measures required in order for geometric techniques to be applicable to real-world data sets.

CR Categories: I.3.3 [Computer Graphics]: Picture/Image Generation; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism–Color, shading, shadowing, and texture I.6.6 [Simulation and Modeling]: Simulation Output Analysis

Keywords: flow visualization, vector field visualization, streamlines, interaction, perception, CFD simulation data

1 Introduction

Demand for visualization solutions for CFD simulation data has grown rapidly in the last decade. This is due, in part, by the interest of manufactures in minimizing the time taken for their production cycle. This objective is realized with the use of software simulation tools to analyze design decisions before constructing real, heavy-weight objects.

At the VRVis research center we collaborate with AVL (`www.avl.com`) in order to provide flow visualization solutions for analysis of their CFD simulation result data. AVL's own engineers as well as engineers at industry affiliates use flow visualization software to analyze and evaluate the results of their automotive design and simulation on a daily basis. The analysis of an engineer includes tasks such as searching for areas of extreme pressure, looking for symmetries in the flow, searching for critical points, and comparing simulation results with measured, experimental results. One pervading message we hear consistently is: users are interested in more interactive control of the flow visualization results–a classic theme in the realm of scientific visualization [Hibbard and Santek 1989]. Engineers as well as users from other disciplines are interested in having a collection of user-options and parameters that allow them to fulfill their individual goals, whether their goals are exploration, analysis, or presentation. Interactive tools facilitate an iterative visual analysis and exploration process i.e., an environment in which the user is able to make rapid decisions and refinement based on visualization results.

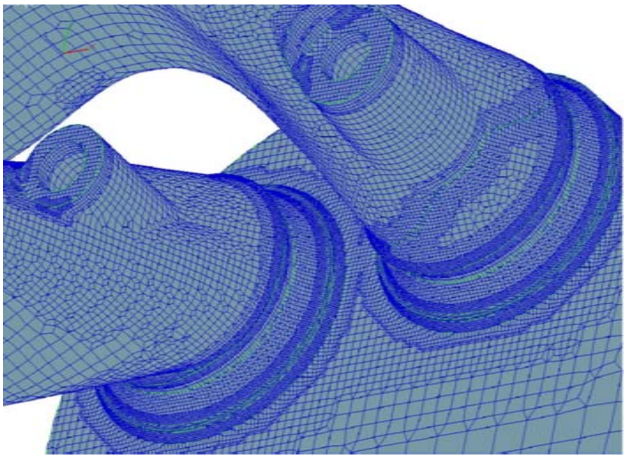

Figure 1: A close-up view of two intake ports in a same CFD simulation grid.The mesh contains multiple, adaptive resolution levels of unstructured grid cells.

AVL analyzes a large, varied collection of data sets ranging from small geometries such as small fluid conduits to mid-range size geometries such as cooling jackets, to large geometries such as automotive exteriors. The geometric sizes of these grids differ by *six* or more orders of magnitude as well as the sizes of the underlying polygons. Hence, the tools used to visualize the simulation results also need to span this range of sizes. We speculate that this difference will increase in the future.

The Versatility of CFD Grids: Another reason the users request more interaction control over the visualization results is due to the fact that CFD meshes embrace a wide variety of components, features, and levels of resolution. To illustrate, we look at Figure 1. We find five adaptive levels of resolution used to evaluate the intake ports: (a) two levels for the top of the ports, (b) approximately the same two levels of detail plus an added layer of finer resolution grid cells for the rings around the base of the ports. The facets in the flow source are approximately 1000–2000 times larger than the finest resolution facets at the base of the intake ports. These grids are a daily experience in the industrial CFD community. Our goal is to provide flow visualization solutions that are equally as versatile and adaptive as the grids themselves.

Perceptual Challenges: A large amount of flow visualization research literature addresses two-dimensional visualization techniques. This is partly because flow visualization on boundary surfaces and in 3D presents additional perceptual challenges such as occlusion, lack of directional cues, lack of depth cues, and visual complexity. Most of the CFD simulation grids at AVL are unstructured and three dimensional. Although engineers often use 2D slices through the 3D meshes during analysis, there is a strong interest in 3D and boundary surface visualization techniques that address the perceptual problems mentioned above.

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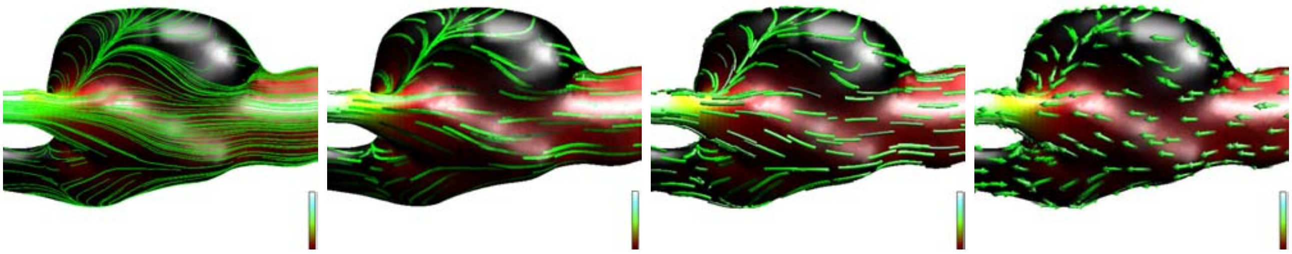

Figure 2: The visualization of blood flow at the surface of an aneurysm: (left) geometric flow visualization using streamlines (middle-left) oriented streamlines–described in Section 3 and (middle-right) streamlets–also described in Section 3, and (right) streamcomets–in Section 5.

2 Related Work

Four different approaches are widely used in flow visualization [Post et al. 2002]. Our work falls into the geometric flow visualization category of techniques. These approaches often first integrate the flow data and use geometric objects in the resulting visualization. The objects have a geometry that reflects the properties of the flow. Examples include streamlines, streaklines, streamsurfaces, and timelines. Not all geometric objects are based on integration. Another useful geometric approach is generating isosurfaces, e.g., with respect to an isovalue of pressure or magnitude of velocity. A thorough description of flow visualization techniques as well as our classification is presented by Laramee et al. [Laramee et al. 2004a] and Post et al. [Post et al. 2002]

3 Oriented Streamlines and Streamlets

One of the drawbacks of conventional streamlines is the lack of flow orientation (upstream vs. downstream direction) depicted in a still image. Our system incorporates an oriented streamline implementation. Oriented streamlines convey the downstream direction of the flow by varying the opacity as a function of particle trace evolution. In other words, the further downstream an integration path is traced, the higher the opacity of the streamline. This can be implemented by giving the streamlines a finite width, either automatically or through user-defined parameters, and using semi-transparent polygons in order to depict an oriented streamline (Figure 2, middle). Arrow heads could also be used to achieve the same effect. However, arrow head glyphs can lead to visual clutter without careful treatment.

Attention must be paid when rendering oriented streamlines on boundary surfaces in order to prevent artifacts resulting from overlapping streamline and boundary surface polygons. These artifacts can be avoided through the use of OpenGL's polygon offset functionality. The result is similar to that of OLIC (Oriented Line Integral Convolution) [Wegenkittl and Gröller 1997; Wegenkittl et al. 1997]. One important difference is that OLIC is based on a traditionally slower approach derived from LIC. Also OLIC is more suitable for the visualization of 2D vector fields.

For the case of unsteady flow, drawing a continuous particle path using a single time-step of the data set can be considered misleading. This is because no particle actually traces such a path. For the case of slices and surfaces, the visualization becomes even more problematic because a component of the vector field is taken away, namely that component orthogonal to the slice or surface, absent after a projection onto the slice or surface. One approach to handling this is through the use of streamlets (short streamlines). Figure 2, left-to-right, shows the use of streamlines, oriented streamlines, streamlets, and streamcomets all applied to the same data set. The data set in this case is simulation data coming from blood flow through an aneurysm.

4 Animated Streamlines

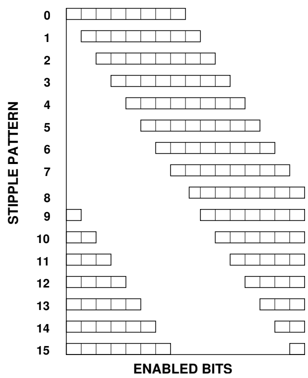

Figure 3: The 16-bit stipple pattern series used for animating streamlines in real-time, based on OpenGL 1.1.

Here, we use a stippling approach to animate streamlines such that the downstream direction of the flow is depicted. The advantage here is that the stippling approach is supported by OpenGL 1.1. and commodity graphics hardware. Thus real-time frame rates can be achieved even for large numbers of streamlines as well as platform independence. Anti-aliasing, also supported by the graphics hardware, can be added to visually enhance the results at very little overhead.

We apply a line stipple pattern to streamline paths. Each streamline is rendered using one of 16 stipple patterns shown in Figure 3. In order to add animation, we simply shift the stipple pattern applied to the integral paths at rendering time [1]. This approach is reminiscent of that used by Jobard and Lefer [Jobard and Lefer 1997b] or Berger and Gröller [Berger and Gröller 2000] where a color-table look-up approach is used to animate the streamlines. One important difference is that the technique here applies well to 3D flow.

Without special handling, geometric techniques can also suffer from some of the same perceptual problems that direct flow visualization can. One means by which to focus on a particular subset,

[1] For supplementary images and MPEG animations, please visit: `http://www.VRVis.at/scivis/geometricApproach/`

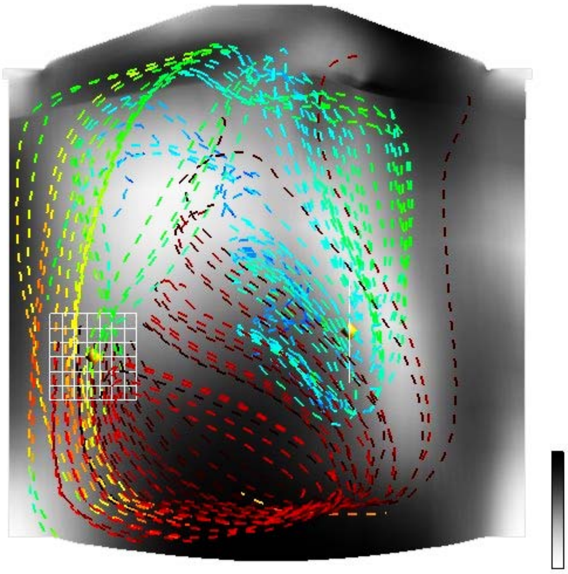

Figure 4: The visualization of tumble motion using animated, dashed streamlines. Two seeding planes are used: one seeding color mapped streamlines, the other emanating red streamlines. A gray-scale mapped slice serves as context information.

area of interest, or feature of a flow field is via a streamline seeding strategy. In general, three popular streamline seeding strategies are often used: (1) *image-based* seeding strategies such as that described by Turk and Banks [Turk and Banks 1996] or the evenly spaced-streamline seeding strategy presented by Jobard and Lefer [Jobard and Lefer 1997a], (2) *topological* or feature-based, seeding strategies such as those presented by and Lf̈felmann and Gröller [Löffelmann and Gröller 1998], Sanna et al. [Sanna et al. 2000], or Verma et al. [Verma et al. 2000] and (3) *interactive* seeding strategies using a streamline seeding rake used by Bryson and Levit [Bryson and Levit 1992] or Schultz et al. [Schulz et al. 1999]. Our approach falls into the third category–an interactive streamline seeding strategy. Users would like full control over which subsets of the vector field to highlight in order to highlight both desirable *and* undesirable characteristics of the flow.

Our seeding tool provides the user with several interactive degrees of freedom (DoF): three translational, scaling, rotational, and resolution control. These interactive DoFs are required to investigate the results of CFD simulations because the meshes from CFD embrace a wide variety of components, features, and levels of resolution.

Figure 4 shows animated-dashed streamlines used to visualize tumble motion [Laramee et al. 2004b]. Tumble motion is the name given to an ideal pattern of flow within the combustion chamber of a gas engine. The sparser animated-dashed streamlines allow the user to see through the volume. Furthermore, the implementation is simpler than the dash tube technique of Fuhrmann and Gröller [Fuhrmann and Gröller 1998].

5 Streamcomets

Streamcomets are an extension of the streamrunner [Laramee 2002]. Streamcomets follow a very intuitive metaphor. They offer four interactive DoFs as shown in Figure 5. The user is given interactive control over: (1) the position of the head along the integral path, (2) the diameter of the comet head and comet tail, (3) the length of the semi-transparent comet tail, and optionally (4) the animation speed of the comet along the path of integration. Coupled with more interactive degrees of freedom, streamcomets offer the advantage of showing local flow direction and curvature for static images. There is strong evidence to support the notion that flow visualization objects that show the direction of the local vector field improve the user's ability to identify critical points and understand particle advection paths [Laidlaw et al. 2001]. We also apply a semi-transparent function to the comet tails and give them a glowing effect. The alpha value along each comet tail is a function of the distance to the comet head i.e., the further away from the head, the more transparent the tail. The semi-transparency uses a standard OpenGL blending function in conjunction with back-to-front ordering of polygons. A useful feature is the option of animating the streamcomets. Conceptually, animating the streamcomets such that the comet head position is automatically incremented along the path of integration, acts as a visual search function. The viewer is able to use the animation to search for optimal comet head positions. This is very useful when the user is not sure where to position the head, searching for interesting features in the flow field, or optimizing the other interactive degrees of freedom. We also give the user the option of interactively adjusting the animation speed.

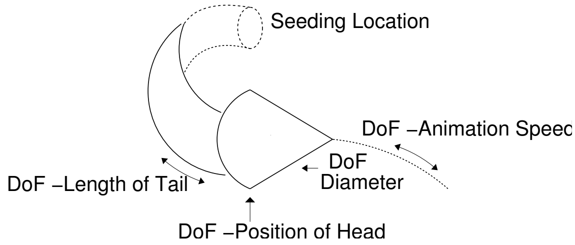

Figure 5: The streamcomet promotes four interactive degrees of freedom: (1) the position of the comet head along the path of integration, (2) the diameter of the comet head and tail, (3) the length of the comet tail, and optionally (4) the animation speed of the comets

We do not propose the streamrunner and streamcomet as standalone features. They are meant to be combined with other classic, 3D interaction techniques such as rotation, scaling, and translation. Additional important features we have included are: the option of choosing a non-uniform coloring scheme so colliding geometric objects can be more easily distinguished, turning on or off semi-transparent or wire-frame context information, and adjusting the streamline seeding density in the flow field. The more streamcomets added to the scene, the more likely the user is to face perceptual issues. We recommend restricting the number to one hundred or less as a rough guide.

6 Results

Performance times depend on the number of streamlines. Performance times for the animated streamlines are given in Table 1. Performance was evaluated on a machine running Red Hat Linux with a 3.2 GHz Intel Xeon dual processor, 2 GB of RAM, and an *NVIDIA Quadro FX 1300* graphics card. Note that the frame rate also varies as a result of caching. Anti-aliasing adds very little overhead since it is built into OpenGL 1.2 and hence is supported by most graphics cards. As we see, the stippling approach allows animation of thousands of streamlines in real-time. Furthermore, we have not employed display lists to increase the frame rates. Figure 6 shows two seeding planes inside the combustion chamber of a piston valve. The seeding plane in the top (foreground) has streamcomets emanating from it. The seeding plane in the middle (background) seeds shaded streamlines. We emphasize the importance of the user's

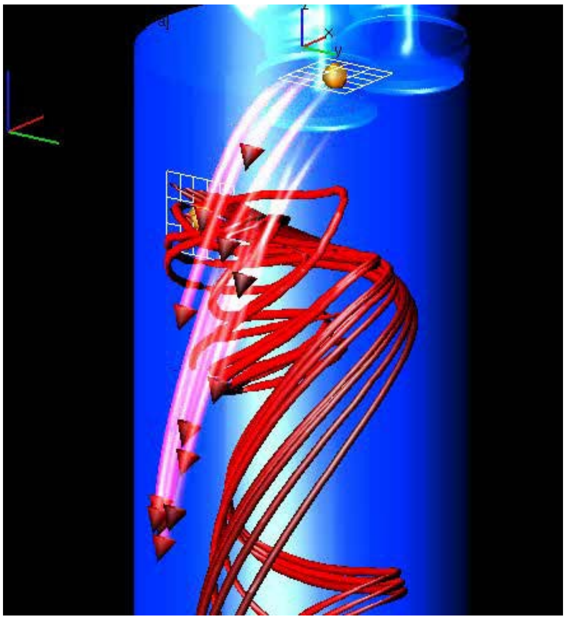

Figure 6: Two seeding planes in the combustion chamber of a piston valve: one seeding streamcomets, the other seeding shaded streamlines.

no. of streamlines	with anti-aliasing	without anti-aliasing
10	101	101
100	101	101
1,000	64	66
2,500	35	40
5,000	20	24
10,000	11	14

Table 1: Sample frame rates for the animated streamlines in frames per second.

ability to resize the streamcomets along arbitrary dimensions when zooming in and out of the data sets. It is important to note that changes to the diameter of the comet heads apply to the entire collection of streamcomets, and are not applied on a per-comet basis. Applying size changes to individual comets would lead to misleading visualization results, e.g., the user may interpret different comet head sizes to be a reflection of scalar properties inherent in the flow field.

7 Conclusions and Future Work

The added interaction provided by our geometric flow visualization techniques is very useful for flow visualization in 3D and within the domain of versatile grids associated with CFD simulations. This is because they are based on geometric primitives that are more suitable for the visualization of 3D flow than approaches based on color-mapping, glyphs, or textures only. The user control afforded by the streamcomets as well as the intuitive metaphor on which they are based makes them more versatile for 3D flow visualization than previous techniques. Furthermore, the simplicity of our approaches makes them strong candidates for inclusion in other flow visualization software packages. The approaches described here have been included in a cross-platform, industry-level visualization application for the analysis of CFD simulation data. These geometric objects give a new level of control over to users investigating a vector field. We encourage the reader to view the animations at the given URL.

Future work could go in several directions including: (1) an implementation prototype of the streamrunner and the streamcomet for unsteady flow visualization including the introduction of a *pathrunner* – the unsteady equivalent of a streamrunner, a streakrunner – the interactive equivalent of a streakline or (2) a formal HCI evaluation of the perceptual effectiveness of the streamrunner and streamcomets for 3D flow visualization.

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