



Visualization of Fluid Flow Data

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Complex 3D fluid flow phenomena are examined using the Stardent AVS software environment with local extensions adding new exploratory techniques. Interactive stream ribbon function generation and various visual attributes are shown to give additional information about flow field data.

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NUMERICAL FLOW FIELDS

In the context of physical testing or in the numerical simulation of 3D fluid flow, large quantities of data are generated, posing serious problems for effective visualization. For example, a 3D experiment with three velocity components, defined on a $100 \times 100 \times 100$ grid, stored as 64-bit floating point numbers, requires 24 Megabytes of storage [2],

It is important to utilize derived representations of such data, with a hopefully interactive derivation process, to gain a full understanding. Simply displaying the data directly (1 million small arrows?) would not be helpful. Abstracting the data through post-processing techniques during visualization allows for interactive investigation, and creates rich, meaningful images of the flow data. What is desired is the comprehension of the spatial structure of the flow, using 3D animation.

VECTOR PLOTS

Drawing small directional arrows indicating the direction and speed of flow is common in 2D flow visualization. A vector arrow plot of some 2D segment of the 3D flow is useful, particularly if the sampling points can be moved interactively. This compensates for keeping the number of arrows low for visual clarity, while getting to interesting areas of the flow by manual positioning. The main problem, however, is that the arrows show the velocity at discrete points in the flow data. To create a more intuitive picture of the flow, streamlines are used [1].

ANIMATING STREAMLINES

In the case of steady-state non-uniform fluid flow, a streamline is an imaginary curved line following the flow, such that at any instant in time, no fluid is crossing the line. Such streamlines are also known as flowlines or a line of flow [3]. If several streamlines are shown at once, a good impression of the flow can be obtained. Further, if groups of streamlines are arranged in bundles, with some geometric cross-section such as a circles, they may form "stream-tubes". Some researchers have extended this idea to create bundles in the form of bubble trains, deforming spheres, sheets, or ladders [5].

The streamline function used for this paper is the standard "stream lines" module in AVS, which takes as input the vector field, and generates a set of geometric polylines, using Runge-Kutta integration at user-specified time intervals.

Once the streamlines are known, the lines may be animated by coupling the line representation to an "animated lines" function, which displays in quick sequence line segments of equal time step along the streamlines. As the velocity varies, some lines will appear to move faster than others, given equal time increments.

INTERACTIVE STREAM RIBBONS

A ribbon is created by centering a chain of triangles along the streamline, with constant width, with the ribbon edges equidistant from the streamline centre. The use of stream ribbons creates a much clearer 3D shape, where lighting and shading can help to explain the depth and orientation of the streamline.

In this implementation, the streamline gives the direction and path of the ribbon, but does not completely define the ribbon cross-section axis on its own. Stream ribbons have been described as a method to show other topological features, where the feature is sampled in such a way as to define the ribbon orientation [2], Dr. Pagendarm has suggested the implementation described here, where ribbon orientation is defined by vorticity, and the ribbon growth used in animation [4].

Vorticity is a vector quantity whose direction is perpendicular to the velocity vector at any point in the flow. The magnitude of the vorticity vector is an indicator of the degree of rotation in the flow, and hence the presence of vortices [3]. The vorticity is computed by taking the partial derivative of each velocity component within a nearest neighbour cell region.

The visualization development tool, AVS, contains a "vector curl" module, that computes vorticity from a velocity field by the following equations:

$$\text{new_dx}[X][Y][Z] = (\text{dz}[X][Y+1][Z] - \text{dz}[X][Y-1][Z]) - (\text{dy}[X][Y][Z+1] - \text{dy}[X][Y][Z-1])$$

$$\text{new_dy}[X][Y][Z] = (\text{dx}[X+1][Y][Z] - \text{dx}[X-1][Y][Z]) - (\text{dz}[X+1][Y][Z] - \text{dz}[X-1][Y][Z])$$

$$\text{new_dz}[X][Y][Z] = (\text{dy}[X+1][Y][Z] - \text{dy}[X-1][Y][Z]) - (\text{dx}[X][Y+1][Z] - \text{dx}[X][Y-1][Z])$$

It is difficult in traditional streamline displays to represent vorticity, except as additional contour lines. In this implementation, vorticity is shown visually as the surface normal of the streamline ribbon. As an option, the ribbon normal can be tilted to be orthogonal to the vorticity vector.

An alternative method for the creation of stream ribbons is to connect two closely spaced streamlines together. This is simple to implement, but has trouble when the two lines diverge [2],

A recent paper [5] describes the use of surface-particles to represent a variety of surfaces. As with ribbons, vorticity is used to control the surface normal of each particle, for the purposes of shading. A large number of particles are needed (34,000 in one case) to represent a ribbon. Although different approximations are involved, the ribbon approach is much more memory and compute-time efficient, allowing interactive control, and can also be texture mapped or annotated with additional information.

RIBBON ANIMATION

The ribbons may be animated in several ways. First, the initial seed points for the streamlines may be varied over time, with complete ribbon generation along streamlines at each seed position.

Second, the number of equal time integration steps passed through to display can be varied from a small number of steps to several hundred steps, creating a "growth" movement. This gives a visual indication of relative speed, as some ribbons grow faster than others. The ribbon generation is parametric over display length, such that the growth can be controlled from an interactive dial or other process.

Thirdly, a texture is applied to the ribbon surface, showing either solid colours, a checkerboard pattern, or shaded arrows, including annotation. The relative position of the texture along the linear axis of the ribbon can be varied with an interactive dial or another process, to create a texture "crawl" along the ribbon.

This extension technique to the AVS system is available for demonstration from Stardent. (US Patent applied)

CONCLUSION

The ribbon representation for streamlines in 3D fluid flow fields is a general technique, adding additional information to interactive flow visualization. The AVS system was used as the prototyping environment, allowing most of the functions described in this paper to be implemented in 1.5 days. By separating file format access, field manipulations such as vorticity, 3D rendering and display into separate software modules, only code directly relating to describing the ribbon representation was needed in the development.

REFERENCES

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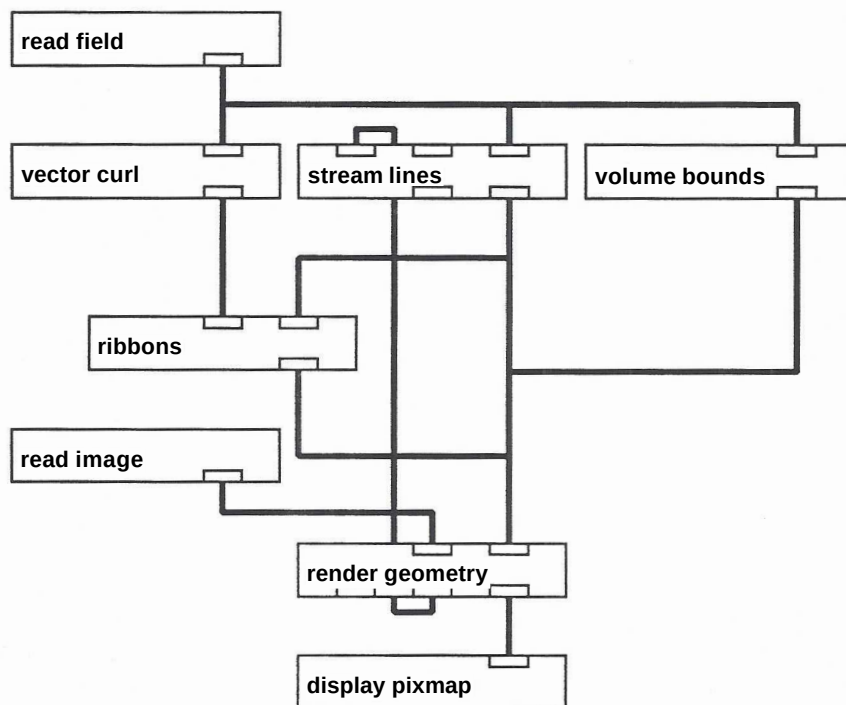


Figure 1. Base AVS data flow network, showing relationships of key algorithms. Data flow is from top to bottom, with input ports shown on the top side of module boxes, and output ports on the bottom. The stream lines module sends results directly to the display routines, and in addition provides input to the ribbon generation routine. Interactive streamline positioning is provided by the upstream flow connection from "render geometry" to "streamlines".

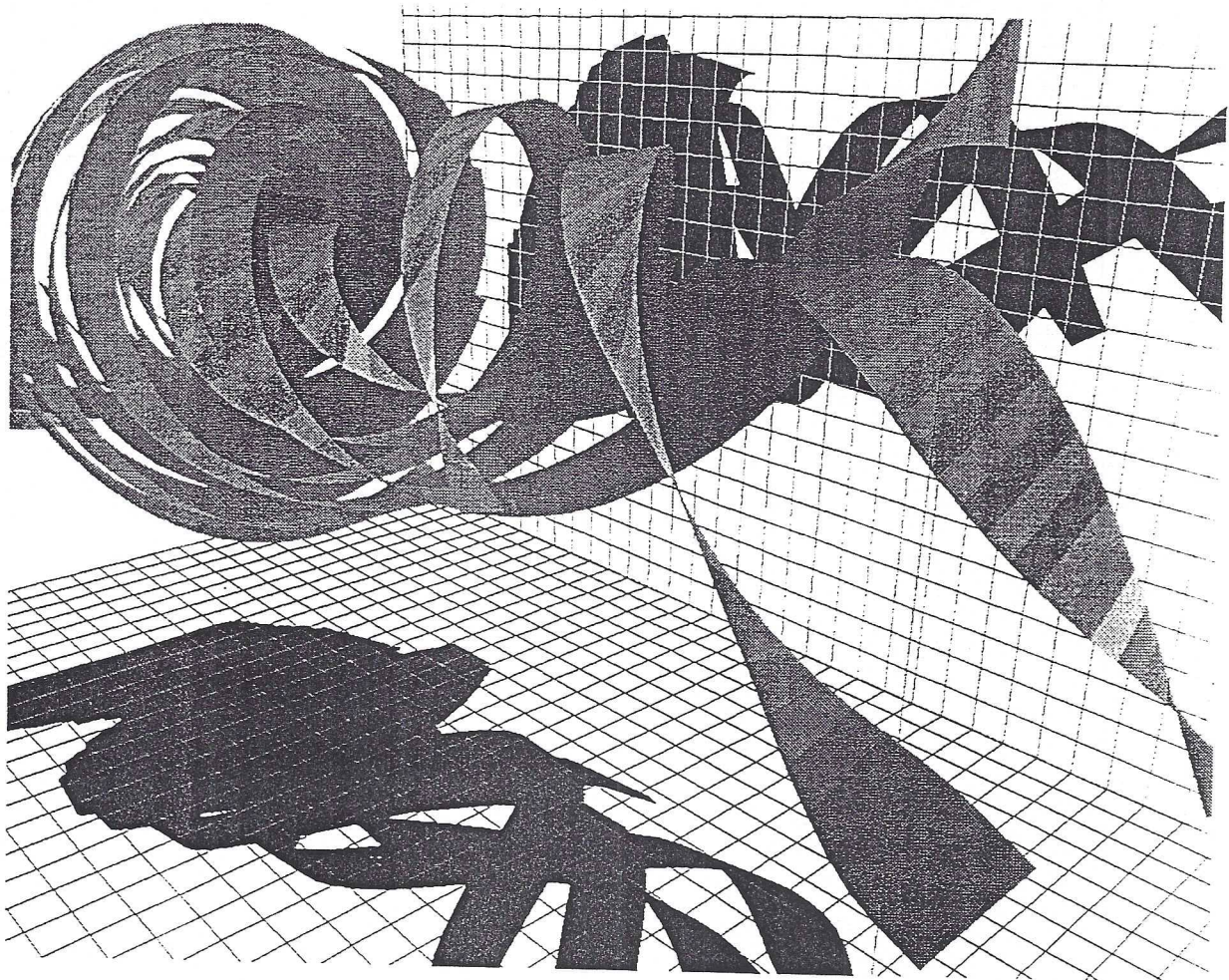


Figure 2. Ribbon display of 3D fluid flow field. Streamline function controls the path of the ribbon, while surface orientation is derived from flow vorticity.

