

DEVELOPMENT OF A VIRTUAL SCIENTIFIC VISUALIZATION ENVIRONMENT FOR THE ANALYSIS OF COMPLEX FLOWS IN THE CARDIOVASCULAR SYSTEM

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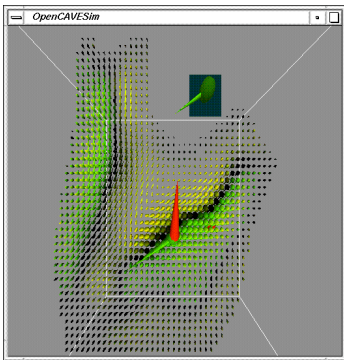


Figure 1: Single Plane of Flow Data

The user controls the red cone which is used to highlight a point in the flow for in-depth analysis. The highlighted point is enlarged and is shown above on a pop-up display.

Scientific Visualization Methodology

The scientific visualization software is designed as a tool for *interactive* simulation and analysis. As such, the single most important aspect of the software is its user-controlled design. The scientist can move through the tens of thousands of data points, and isolate points/areas of particular interest or concern, and then create a set of iso-points based upon the point that they chose. Once a point is highlighted, it is enlarged such that it stands out from the rest of the points, and is shown above on a pop-up display. These features are shown in Figure 1, which is a single two-dimensional plane of 61 x 61 data points. Once the user has selected a point in the data set, there are various options for exploring the various parameters associated with the point. For instance, a contour surface based upon a stress tensor with a corresponding set of values associated with each point can be generated with the push of a button, as is shown in Figure 2. The contour is made up of cylinders of equal height, with the two horizontal axes scaled to the in-plane values of the tensor, and the color according to a cross-correlation term. By clicking a second button, a set of iso-points is created as colored spheres, such that the values of a new parameter at each point lies close to the value at the selected point (Figure 3).

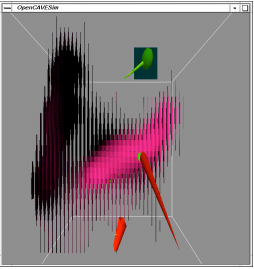


Figure 2: Stress Tensor Contour Plot

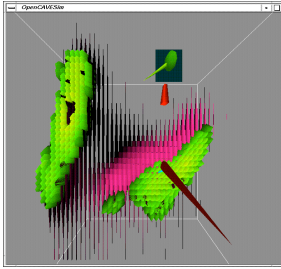


Figure 3: Stress Tensor Contour Plot with Iso-points

In the representation of highly-complex data with multiple inter-related parameters, it is difficult to represent each parameter in such a way that they are distinguishable from one another. Our system utilizes "glyphs" (from the Egyptian term, hieroglyphics) to create a useful tool for interactive scientific visualization and analysis. Glyphs are objects or symbols used to represent a quantity or entity. The glyph designed for the heart flow simulation consists of a cone attached to an ellipse, as shown in Figure 4. For the heart flow simulation, the cone represents the magnitude of the velocity at a single point, and its orientation the direction. The ellipse is scaled to the values of the symmetric Reynolds stress tensor at that point, with the lengths along the axes perpendicular to the axis of the glyph representing the two in-plane Reynolds stresses, and the axial length corresponding to the cross-correlation term between the two. The color of the glyph represents the magnitude of the vorticity, with brighter colors indicating severe or extreme values.



Figure 4: Heart Flow Glyph

APPLICATION TO HEART FLOW

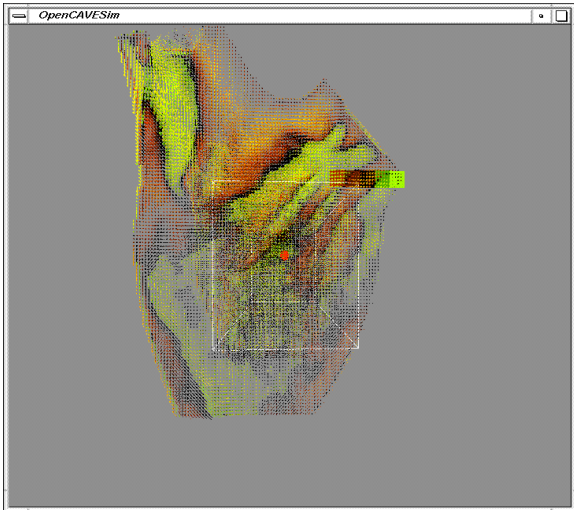


Figure 5: Five-Layer 3-D Heart Flow Steady-State Distribution

The program displays five separate planes, each composed of a grid of 125 x 125 points, which are displayed as glyphs. The areas that appear to be denser than others,

those near the top, are regions of high Reynolds stress. The vorticity is represented by the color of the glyphs, with brighter colors signifying higher vorticities. The user can move through the simulation and explore the obtained data.

Introduction

The experimental investigation and analysis of complex vortical flows has always been a very tedious task. The level of complexity increases significantly in the case of spatio-temporally developing flows that involve the interaction of vortices with deformable walls and structures. These types of flows exist in the cardiovascular system and especially in the case of the flow through mechanical heart valve and inside the heart left ventricle. The analysis of such complex systems requires a powerful and adaptive scientific visualization environment. Scientific visualization techniques have been used extensively in the representation of velocities, flow field properties such as vorticity and helicity, instantaneous streamlines, iso-surfaces, and volume slices. These simulations are quite effective in providing a platform for qualitative assessment of highly-complex systems, as they make use of the inherent ability of the human brain to recognize patterns and correlations between parameters, and to make inferences based upon visual information. Virtual environments are becoming increasingly popular among the scientific visualization community, as they create the illusion of immersion within the system, particularly in biomechanical and medical applications.

Background

Time-Resolved Digital Particle Image Velocimetry (DPIV) is a non-intrusive flow measurement technique that was used to obtain spatio-temporal descriptions of 3-D flow patterns with high spatial and frequency resolution within a simulated left ventricle. The purpose of this project is to integrate these tools with virtual reality (VR) and create an interface between experimental data from (DPIV) and 3-D virtual reality systems, as the data analysis process is limited by current visualization methods that are generally capable of only 2-D representations. Flow visualization of the heart for evaluation of long-term performance of artificial heart valves is an important topic in blood flow engineering and heart biomechanics. By accurately determining the hemodynamic behavior of these valves, improved designs can be developed. Advanced 3-D visualization of heart flow mechanics will give increasingly valuable insight into the fluid mechanics of mechanical heart valves, as well as to modes of

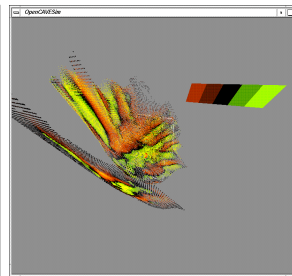


Figure 6: Top View of 3-D Heart Flow Model

The view is from above the mitral side. The vorticity map is given by the legend at the top right.

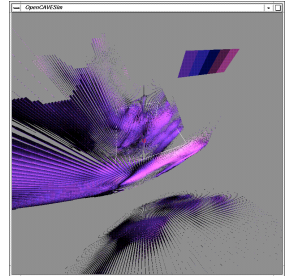


Figure 7: Top View of Reynolds Stress Contour

The symmetric tensor is mapped as scaled cylinders with the color representing the cross-correlated term.

Results and Conclusions

It is demonstrated that the integration of a sophisticated non-intrusive flow diagnostic tool with the visual observation power of VR can significantly enhance our ability to analyze and understand complex vortical flow fields. This is a critical feature when better understanding of cardiovascular flows can guide the improvement of the design of mechanical heart valve implants. Future work involves the expansion of the virtual scientific visualization environment to applications in other fields, including materials science, aerospace, and ocean engineering, as well as many others.

Acknowledgements

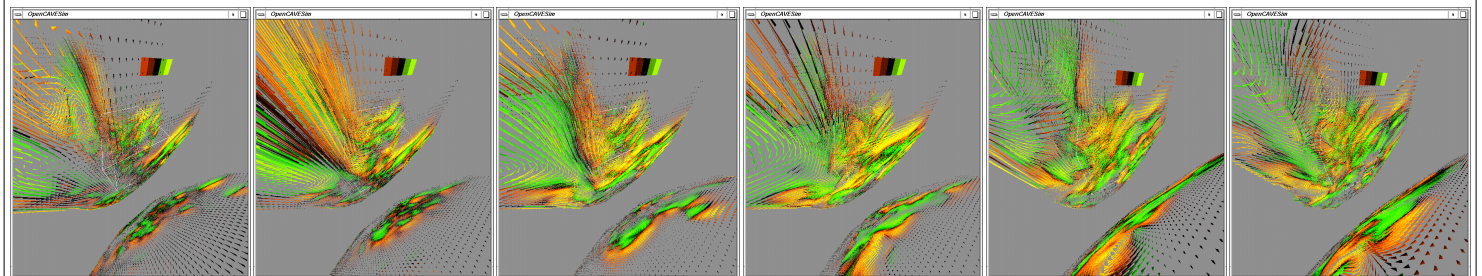
The first two authors would like to thank Dr. Ronald Kriz, John Kelso, and the VT CAVE™ staff for their support in the development of our VR simulations.

Facilities/Methodology

The Virginia Tech CAVE™ (Cave Automated Virtual Environment) system was used to develop an immersive, 3-D environment for visualization and analysis of DPIV results from the flow inside a heart chamber. The CAVE™ system is a 10'x10'x9' set of screens onto which images are projected by three cameras. Stereo goggles, worn by the CAVE™ user, shutter back and forth between each eye, giving the illusion of 3-D immersion. The user controls his/her perspective of the images using the "CAVE™ wand", a stereo device that lets the user move through the simulations, such that they are "immersed" in the virtual representation. The CAVE™ system can also be networked such that clinical interaction can be conducted via the Internet in real time using CAVE™ systems and SGI computers.

Time resolved three-dimensional velocity and Reynolds stress data are imported into the virtual environment using software that we developed in C++, OpenGL™ and VRML in order to convert the spatial coordinate and 3-D velocity data from the PIV system into a series of glyphs in three-space to represent the flow. Each time step allows for instantaneous changes in the velocity magnitude and direction associated with each coordinate, creating a time-dependent series of frames that depicts the state of the velocity field as it changes in time, or frame-by-frame as controlled by the user in the CAVE environment. The user can then move through the flow and view the flow field from the perspective of a particle in the field.

The series of pictures shown below represent six time-steps of an unsteady heart flow data set. The user is viewing the simulation from the top of the heart on the aortic side. The arrows point up and out of the picture at the top left represent the outflow of blood through the aorta. The arrows point in the direction of the flow at each point in space and time, and the color is scaled to the value of the vorticity,



according to the legend shown in the upper right-hand corner. Notice how easily the vortices can be followed as they move through the heart for multiple layers of data. The scientific visualization system is an excellent tool for monitoring such parameters at particular points in space or in the volume as a whole.