BED-Vol. 50, 2001 Bioengineering Conference
ASME 2001

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

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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 cardio-vascular system and especially in the case of the flow through mechanical heart valve and inside the heart left ventricle (LV). The analysis of such complex systems requires a powerful and adaptive scientific visualization environment.

BACKGROUND

Tools for visualizing velocities, flow field properties such as vorticity and helicity, instantaneous streamlines, unsteady streaklines, iso-surfaces, and volume slices, have been widely used in the past. Quantitative 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.

Time-Resolved Digital Particle Image Velocimetry (DPIV) is a non-intrusive state of the art flow measurement technique that has bee developed over the past ten years. A major advantage of DPIV over preexisting methods is the ability to provide spatio-temporal description of three-dimensional (3-D) flow patterns with high spatial and frequency resolution. This facet allows an improved analysis of the turbulent characteristics of the flow. However, the data analysis process is limited by current visualization methods that are generally capable of only 2-D representations.

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. VR is proving to be an increasingly useful visualization tool in biomedical engineering as non-invasive measurement systems expand their capabilities. For example, MRI scans can be turned into immersive 3-D representations that can give clinicians a major advantage over other methods of visualization. Hodgins et al (1995) are using VR for realistic human body motion simulations1. By linking this technology with existing DPIV data, one creates a true representation of the flow under investigation, for heart valve performance evaluation and analysis. Kaltenborn and Rienhoff (1993) have regarded VR as a most promising field of application for integration with visualization and simulation of anatomic and biomechanical function in medical education and research. Undoubtedly, advanced 3-D visualization of heart flow mechanics will give increasingly valuable insight into the fluid mechanics of mechanical heart valves, as well as possible modes of improvement. It is the goal of this study to increase our capability of analyzing and interpreting complex three-dimensional flow fields by taking advantage of the potential of VR environments.

FACILITIES AND METHODS

The Virginia Tech CAVE^{TM} (Cave Automated Virtual Environment) system is currently being used to develop an immersive, 3-D environment for visualization and analysis of DPIV results from the flow inside a heart chamber. This system will provide an advanced simulation of the heart flow observed in laboratory tests, with complete user-oriented control. The CAVE^{TM} system is a 10'x10'x9' set of screens onto which images are projected by three cameras. Stereo goggles, worn by the CAVE^{TM} 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^{TM} wand", a stereo device that lets the user move through the simulations, such that they are "immersed" in the virtual representation. The CAVETM system can also be networked such that clinical interaction can be conducted via the Internet in real time using CAVE^{TM} systems and SGI computers.

Time resolved three-dimensional velocity data are imported into the virtual environment using software that we developed in C++, OpenGL^{TM} and VRML in order to convert the spatial coordinate and 3-D velocity data from the PIV system into a series of arrows in three-space to represent the flow. Each time step will allow for instantaneous changes in the velocity magnitude and direction associated with each coordinate, creating a time-dependent series of frames that will depict 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.

Digital Particle Image Velocimetry (DPIV) provides instantaneous plane velocity measurements of the flow field. Detailed description of the principles of the method can be found in Willert and Gharib (1991), Westerweel (1993). The system used is based on 55Watts pulsing laser that illuminates the area of interest. The flow is seeded with neutrally buoyant fluorescent particles, which serve as flow tracer. A very fast CCD video camera is synchronized with the laser to capture with 1000 frames/sec and 256x256 pixel resolution the instantaneous positions of the particles. The task of the velocity evaluation is carried using conventional cross-correlation between the particle image patterns of two consecutive frames. The interrogation window size was 16x16 pixel and 75% overlapping was used resulting in approximately 3,000 vectors. After removal of stray vectors and interpolation to generate a uniform Cartesian grid the overall accuracy of the method was estimate to be in the order of +/- 0.005m/s. A detailed description of the system is found in Vlachos (2000). For the present work data are acquired along a sequence of parallel planes to allow the reconstruction a volume of the flow field.

RESULTS

Figures 1 through 3 correspond to examples of the application of our virtual world into the analysis of flow visualization data. Although, the objective of VR is to allow us to escape from the two-dimensional visual limitations, ironically a paper presentation is bound to be constrained in single level of observation.

Figure 1 presents a set of animated flow visualizations of the flow under investigation. The visualizations were preformed along a sequence of parallel planes. By placing the acquired animation in our virtual environment we gain the capability to simultaneously observe the time dependent evolution of the flow field in all planes. In addition, the ability to move inside the virtual word provides a wide variety of viewing angles enhancing our perception ability.

Figure 2 shows a conventional representation of the instantaneous flow field downstream the mitral valve, inside the left ventricle. The vectors correspond to velocity distribution, while the color mapping represents vorticity values. Obviously, reconstruction of a volume of data of such a complex three-dimensional flow field would significantly compromise our ability to extract flow features. However, the use of a virtual environment provides to the investigator the ability to "immerse in the flow", move close to small-scale structures in order to focus on the detail or distant him/her-self and observe the global flow characteristics. An example of a detailed view of a vortical structure is shown in figure 3, where the arrows are correspond to the velocities with the vorticity distribution color-mapped on the vector body.

DISCUSSION

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 valves implants.

ACKNOWLEDGEMENTS

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

REFERENCES

1) J.K. Hodgins, W.L. Wooten, D.C. Brogan, and J.F. O'Brien, "Animating Human Athletics," SIGGRAPH 95 Proceedings, Annual Conference Series, pages 63-70. ACM SIGGRAPH, Addison Wesley, August 1995.
2) Kaltenborn, K.F., and Rienhoff, O., 1993, "Virtual Reality in Medicine," Methods of Information in Medicine, Vol. 32, No. 5, pp. 407-417.
3) Westerweel J. (1993): Digital Particle Image Velocimetry, Theory and Application. Delft University Press
4) Willert C E and M Gharib (1991): Digital Particle Image Velocimetry. Experiments in Fluids 10, 181-193 1991
5) Vlachos P. Pavlos (2000): An Experimental Spatio-Temporal Analysis of Separated Flows over Bluff Bodies Using Quantitative Flow Visualization. PhD Dissertation, Virginia Tech.

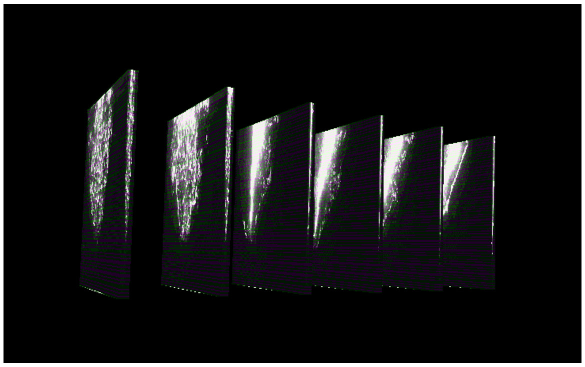

Figure 1: A virtual world demonstrating a three-dimensional reconstruction of the flow from a set of plane hydrogen bubble flow visualizations

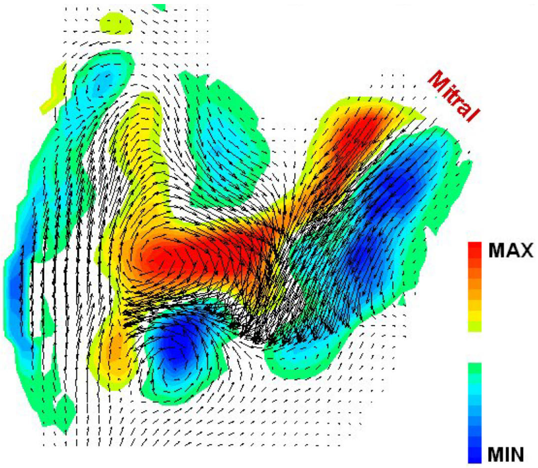

Figure 2: A two-dimensional representation of the velocity and vorticity distribution in the flow field downstream the mitral valve

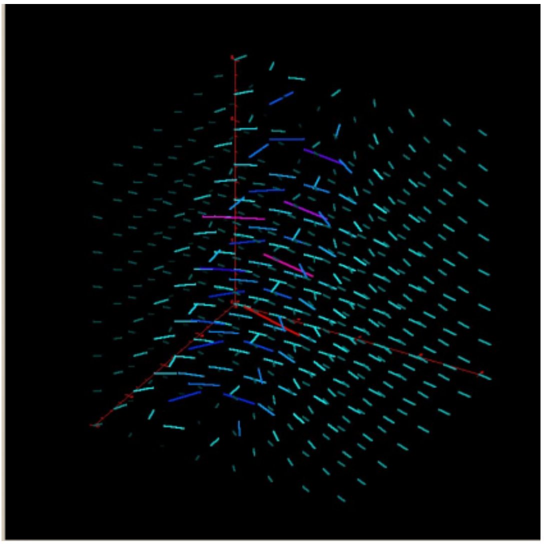

Figure 2: A three-dimensional virtual world corresponding to a detail of the vortical structure velocity distribution. Colors correspond to vorticity values.