Flow Stability and Transition Past an Aortic Valve Using a Hybrid Multicore/Manycore Massively Parallel Navier-Stokes Solver

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Introduction
Since five decades ago, over 50 different designs have been proposed for mechanical and bioprothetic valves. A optimal prosthetic must minimize the blood damage, thrombosis and thromboembolism and yet sustain a lifetime durability. Mechanical heart valves have a superior durability compared to bioprosthetic valves, yet they allow poor biocompatibility and hemodynamics. Improving heart valve prostheses design necessitates an in-depth understanding of the reach and multi-scale phenomena in the vascular flow system. Among four types of valves in human heart, we aim at optimizing the design of aortic valve, which connects left ventricle to the ascending aorta. Pulsatil turbulent flow in the aortic soft tissue offers enormous flow phenomena in various scales of space and time. To capture the principal modes of these nonlinear system, we aim at decomposing the instability mechanisms. One set of essential coherent structures which ultimately break down to turbulence are those initiated at accretion phase in the cardiac cycle. In this work, we focus on this phase in a biogical sense, that is, only two dimensional modes of instability and separation are desired. As it is depicted in the Fig., one observes very rich dynamics, including vortex pair interactions, shear layer instability, cavity finite core vortex and shear layer interactions and convoluted wake Instabilities. Secondary modes of motion are oftentimes conjugated to any of the mentioned interactions as well.

GPU-accelerated High-Order Turbulent Flow Solver
Flow and Blood Flow in Biomedical Engineering. Simulations using the GPU-accelerated parallel Navier-Stokes solver [2,3]. In these concerning, accurate sharp-interface immersed boundary methods are chosen for GPU programming and it is interfaced via a flexible interface to immersed boundary methods. Our solver is designed to be flexible and can be adapted as necessary. It is critical for direct numerical simulation of turbulent and transitional flows.

Instability Mechanisms in BMH-like Systems
A model for the aortic root has been adopted from Rami et al. [4]. A bloodlet mechanical heart valve (BMH) often evolves three parallel jets separated by the rigid leaflets. Interaction of these jets after the valve triggers acceleration phase instabilities. Active primary mechanisms include shear-layer and wake instabilities; see Fig. 3. The present forward modeling disregards pulsatile and 3D swirling modes of fluid motion, yet, it is expected to capture principal wake and cavity eigen modes and their interaction with the bounding walls. Energy exchange between these modes draws a system of rich vortex dynamics, any of which can play a pivotal role in the biocompatibility of the valve system. A vortex of controlled strength can be advantageous by eliminating blood cell trauma, however, a redefining free stream vortex pair may provide a considerable amount of exposure time for platelet activation. A thorough analysis of this dynamical system is required for a better understanding of the blood flow phenomena in the acceleration phase and their evolution in later stages of cardiac cycle. Yet, a handful of interesting events are shown in the figure. Side jets exiting from the BMH invoke a primary vortex roll-up in both sinus and commissure cavities. These intrinsic vortex rolls will instigate a secondary counter-rotating vortex in the cavity. A bilateral pair of von Karman vortex streets depict the characteristic phenomena past the BMH valve, emitting clusters of free-stream Lagrangian coherent structures. A high-order and scale-resolving simulation is necessary to capture some of the small-scale yet large impact aspects of the system, e.g., separation regions on the valve’s leaflets.

Instability Mechanisms in BVI-like Systems
Instability mechanisms in the BVI-like configuration are different than those of BMH-like setup. As it is visualized in Fig. 4, there is only one central jet entering the valve system. Flow further accelerates moving over the forward-facing-step-like valve leaflet. As valve structure has a finite thickness, their downstream can be regarded as a backward-facing-step. Therefore, a region of reverse pressure gradient and flow separation is expected after the valve. This phenomena evolves as a rolling shear layer toward the sinus and commissure cavities. A counter-rotating vortex starts to develop as a consequence of the vortex-roll and the cavity interaction. When the roll front arrives at the trailing edge of the cavity, it may reach the edge of the leaflet. This instability may result in separation, leading the cavity to be a free-vortex like free-stream. The vortex becomes unstable as a result of its interaction with the cavity’s sharp trailing edge. This instability detach the vortex-core from its originating shear layer, shedding the first cavity vortex. This vortex then becomes back in the cavity, injecting kinetic energy to the above-the-valve shear layer at the trailing edge of the leaflet. This energy exchange is captured by the cavity vortex in the stream. The time-scale of this vortex shedding is far less in the commissure side, resulting in an earlier shedding. It is interesting to note that the cavities leading edge does not accommodate almost any circulation, in contrast to BMH-like setup. This can be linked to the swirling modes of fluid motion in the cavity, that required a 3D analysis. It is also worth discussing that there are no traveling waves observed on the aortic walls downstream the BVI valve, as the acceleration jet does not directly interact with the cavity’s trailing edge. This favors a better hemodynamics for BVI, left along the leaflet and blood flow interactions.

Fig. 1. GPU performance of a high-order differential kernel

Fig. 2. Multi-loop hybrid adaptive high-performance computing

Fig. 3. Flow instabilities past a BMH-like configuration

Fig. 4. Flow instabilities past a BVI-like configuration