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

Hadi Zolfaghari[1], Barna Becsek[1], Maria Nestola[2], Rolf Krause[2], Dominik Obrist[1]
[1]ARTORG Center for Biomedical Engineering, University of Bern, Bern, Switzerland
[2]Institute of Computational Science, University of Lugano, Lugano, Switzerland

Università della Svizzera italiana | Faculty of Informatics | Institute of Computational Science

CSCS
Centro Svizzero di Calcolo Scientifico
Swiss National Supercomputing Centre

Introduction

Since five decades ago, over 50 different designs have been developed for mechanical and bioprosthetic valves. A optimal prosthesis must minimize the blood damage, thrombosis and thromboembolism and yet sustain a life-term durability. Mechanical heart valves have a superior durability compared to bioprosthetic valves, yet they allow poor biocompatibility and hemodynamics. Improving heart valve prosthesis design necessitates an exhaustive understanding of the reach and multi-scale phenomena in the valvular 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. Pulsating turbulent flow interacting with 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 acceleration phase of the cardiac cycle. In this work, we focus on this phase in a biglobal 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 instabilities are captured using a high-order hybrid multicore/manycore massively parallel Navier-Stokes solver (IMPACT)[1]. A mass-conserving, accurate sharp-interface Immersed Boundary Method [2] has been used to accommodate flows in the vicinity of complex geometriesOur flow solver is powered with distributed NVIDIA GPUs [3]. CUDA C is chosen for GPU programming and it is integrated via a flexible interface to the FORTRAN flow solver. Double-precision arithmetic accuracy of the solver is sustained on the GPU. This is critical for direct numerical simulation of turbulent and transitional flows.

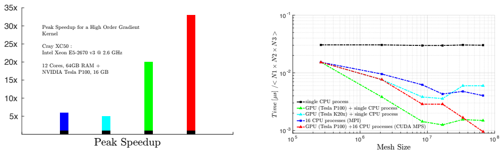


Fig. 1. GPU performance of a high-order differential kernel

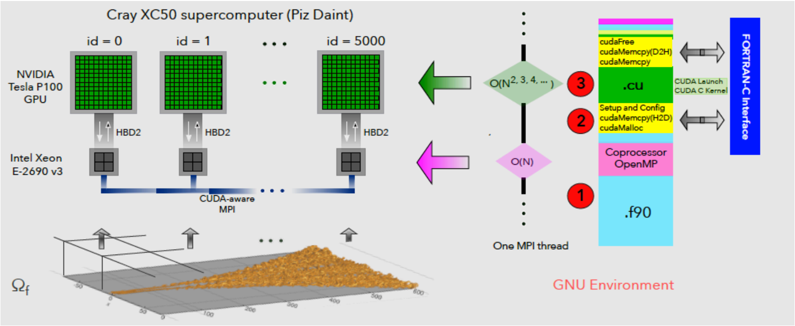
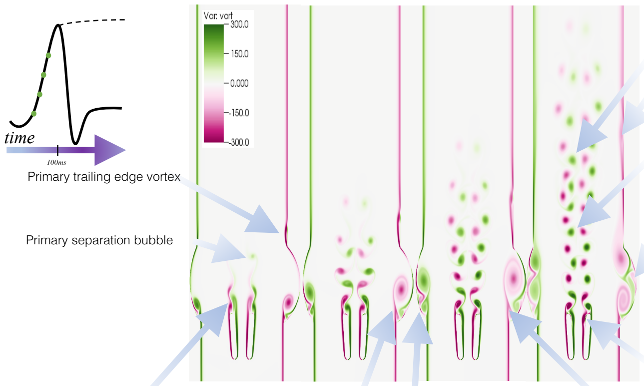


Fig. 2. Multi-language hybrid adaptive high-performance computing

Instability Mechanisms in BMHV-like Systems

A model for the aortic root has been adopted from Rami et al. [4].
A bileaflet mechanical heart valve (BMHV) often evolves three parallel jets separated by the rigid leaflets. Interaction of these jets after the valve triggers acceleration 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 rebounding 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 BMHV 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 BMHV 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.



Primary trailing edge vortex

Primary separation bubble

Vortex pair interactions

cavity's trailing edge vortex

Rebounding vortex

Tertiary separation bubble

Boundary layer separation

Von Karman wake instabilities

Primary rolling-up cavity vortex

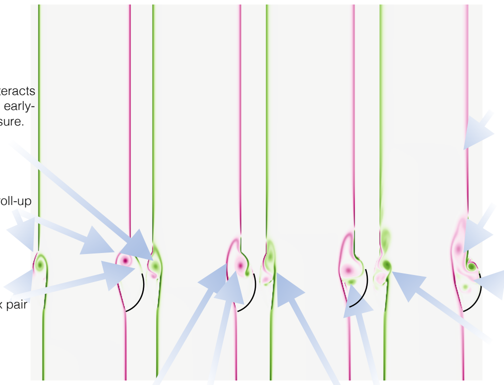
Secondary counter-rotating vortex pair

Cavity vortex – shear layer interaction

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

Instability Mechanisms in BHV-like Systems

Instability mechanisms in the BHV-like configuration are different than those of MHV-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 structures have a finite thickness, their downstream can be regarded as a backward-facing-step. Therefore, a region of inverse pressure gradient and flow separation is expected after the valve. This phenomena evolves as a rolling shear layer towards 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, let say of the sinus, it becomes unstable as a result of it's contact with the cavity's sharp trailing edge. This instability detaches the vortex-core from its originating shear layer, shedding the first cavity vortex. This vortex then bounces back in the cavity, injecting kinetic energy to the above-the-valve shear layer at the trailing edge of the leaflet. This energy exchange yields in freeing the cavity vortex in the stream. The time-scale of this vortex bouncing 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 MHV-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 BHV-like configuration, as the accelerating jet does not directly interact with the cavity's trailing edge. This favors a better hemodynamics for BHV, let alone the leaflet and blood flow interactions.



Rebounding vortex interacts
with the shear layer at early-
stages in the commissure.

Leading edge vortex roll-up

Counter-rotating vortex pair
In the cavity

No traveling waves on the wall,
No trailing edge cavity vortex

Sinus vortex becomes a free-
stream vortex, shedding starts

Secondary unstable modes
In the sinus

Nearly harmonic shedding

Sinus roll becomes unstable.

Sinus finite-core vortex pair

Cavity vortex interacts with the stream-wise shear-layer

Earlier shedding in the commissure

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

hadi.zolfaghari@artorg.unibe.ch
www.artorg.unibe.ch
@CVE_ARTORG
CardioVasc Engineers

ARTORG CENTER
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