8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

DIRECT NUMERICAL SIMULATION OF THE PHYSIOLOGICAL FLOW THROUGH A BILEAFLET MECHANICAL HEART VALVE

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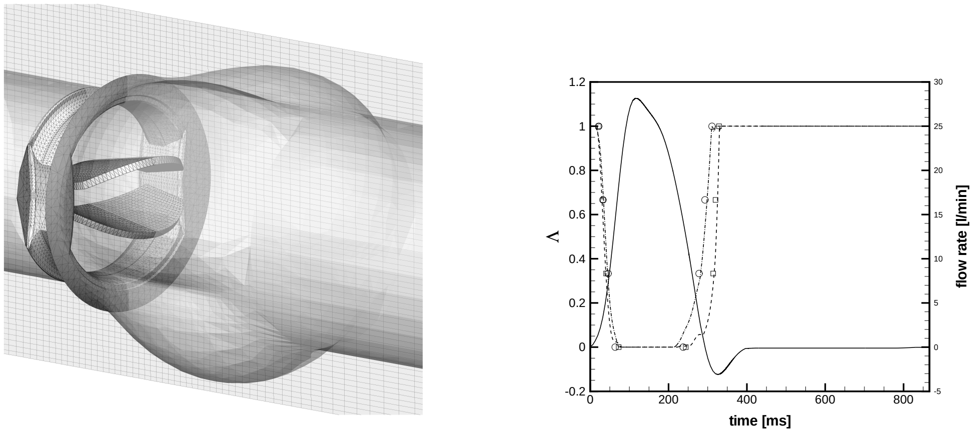
Key Words: *Fluid-Structure Interaction, Immersed Boundary, Mechanical Heart Valve.*

ABSTRACT

Bileaflet Mechanical Heart Valves (MHV) have been used for over two decades and today remain the most widely implanted valve design whenever the natural valve can not be restored to a normal function, thanks to their great durability, good bulk forward flow hemodynamics, and large orifice area which generates small transvalvular pressure drops. Despite their widespread clinical use, the function of these artificial devices is far from perfect. Mechanical stresses of turbulence generated downstream the valve cause problems like hemolysis, platelet destruction, and thromboembolic events arising from the formation of clots and their subsequent detachment. Prevention of these complications requires lifelong anticoagulation therapy, inducing high level of hemorrhage risk. Therefore, there is a need for a better understanding of the flow field in the vicinity of such valves, this being a challenging problem for advanced numerical and experimental methods used in fluid mechanics due to the presence of complex moving geometries and very high velocity gradients both in space and time. The flow field can vary from locally 2D to a complex 3D structure, and since the the Reynolds stress tensor is not invariant under coordinate system rotation, 2D *in vitro* analyses, often conducted with two-component velocity data measured in coordinate system fixed relative to the model and valve orientation, can underestimate the normal and shear stresses. Moreover, to obtain critical information for both the design and evaluation of such artificial organs, blood damage predictive models, accounting for the time varying loading history and the cumulative effect of different stress magnitudes are needed.

In this work, we present an efficient and flexible numerical tool to investigate the evolution of the flow field through a realistic bileaflet MHV. A 3D unsteady flow analysis is performed using Direct Numerical Simulation (DNS) for the solution of the incompressible Navier-Stokes equations. The Immersed Boundary (IB) approach [1], where the presence of a complex boundary is replaced by a time–spatially varying distribution of a forcing term which mimics the effect of the body on the flow, is implemented. The main advantage of this approach is that the forcing can be prescribed on a simple regular mesh (Cartesian), thus retaining all the simplicity and efficiency of the methods developed in that framework, even with complex and moving geometries. A Fluid-Structure Interaction (FSI) algorithm is also developed to achieve the leaflet motion: the forces exerted by the fluid on the leaflets are computed at each time step and applied to the leaflet equation of motion in order to predict the new

leaflet position. Figure 1a shows the aortic root geometry, with the three sinuses of Valsalva placed at equispaced radial positions, the valve geometry, with curved leaflets, and the computational grid used (6.6 millions points). The pulsatile inflow (figure 1b) corresponds to typical physiological conditions under which an adult aortic valve operates. Several complete cycles are simulated. The CPU time for the computation of each complete cycle is about 60 hours on a single P-IV processor, equipped with 1 Gb of RAM. The simulations show the presence of large scale vortices within the field especially in the sinuses of Valsalva and in the wake of the valve leaflets, which are responsible for most of the production of turbulent stress. Ensemble-averaged stream-wise velocity profiles, along with their *RMS*, at different temporal locations, in different sections in the symmetry plane show a good agreement with the experimental results of [2]. The method is very accurate also in capturing the leaflets' dynamics, as shown in figure 1b: the motion of the leaflets, especially during the closing phase, is not symmetric, as observed in experiments (open symbols). Finally, 2D and 3D computed maps of the maximum turbulence shear stress show that, since the flow creates complex 3D structures, the 2D analysis can underpredict maximum shear stresses locally, depending on how much the axes are misaligned with the plane of maximum mean flow shear. All the results confirm the accuracy and the efficiency of the tool developed, which represents a significant advancement of the state-of-the-art of the literature in this field, providing valve developers with useful informations for validating and predicting valve performance in an inexpensive manner. In the final paper, a detailed analysis of the shear-induced trauma will be provided, to describe the blood damage sustained by the red cells not only in terms of magnitude of the acting load and time of exposure to it, but also in terms of load history and duration.



(a) (b)

Figure 1: (a) computational grid (only one every four grid lines is plotted) around modeled valve. (b) time variation of the ensemble-averaged leaflets angular position $\Lambda = \frac{(\alpha_{open} - \alpha)}{(\alpha_{open} - \alpha_{closed})}$ and flow rate: comparison with experimental results of [2].

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