Numerical Simulation of Bileaflet Mechanical Heart Valves in Effect of Cardiac Cycle Lengths

A. V. Nguyen*, R. Verzicco*, M. D. de Tullio**

** University of Rome 'Tor Vergata', ** Politecnico di Bari*

Introduction

• Investigation in prosthetic heart valves and mechanical heart valves have been studied for more than five decades (De Wall et al., 2000; Gott et al., 2003), in the aid to implantation of those artificial devices in cardiac surgeries for replicating the function of the natural valves of human hearts. The patients who get a cardiac prosthetic valve could have a good opportunity of much longer survival with standard quality of life (De Paulis et al., 2005). Since the first successful surgical replacements of diseased human heart valves in 1960 (Braunwald et al., 1960; Harken et al., 1960), the utilities of cardiac prostheses in biomedical engineering have been increasingly developed and advanced, with more than 50 models of mechanical heart valves have been designed (de Tullio at al., 2008). Among those kinds of artificial cardiac prostheses, the bileaflet mechanical heart valve which mimics functions of natural aortic heart valve was majorly designed and produced. In this research the popular St. Jude bileaflet mechanical vavle (Fig. 1) (St. Jude Mediacal Inc., Minneapolis) and the Valsava graft with three sinuses (Fig. 5) are represented to study as they play an important role in both biomedical engineering and scientific purposes.

• An *in silico* investigation of direct numerical simulation (DNS) of flows over the bileaflet mechanical heart valve is investigated in this work. Simulation results include essential fluid flow parameters such as instant velocity contours (Fig. 4, 6), pressure distribution, turbulent shear stresses along the aortic valve provide us understandings of the dynamics of bileaflet heart valves in aortic prostheses as well as blood flow properties in a human heart. This research is focusing on evaluating effects of the changing in pulsatile cardiac cycle length on the blood flow through the prosthetic aortic heart valves. The length of pulsatile cardiac cycle is changed in a wide range (500 ms ÷ 1158 ms) helping us to appreciate the behavior of the bileaflet mechanical heart valves in dynamics aspect.

Methods

- A so-called combination method of Immersed Boundary Method (IBM) and Fluid-Structure Integration (FSI) algorithm is employed to obtain physical information of the blood flow over the bileaflet mechanical heart valves in full pulsatile cardiac cycle lengths.
- Fluid (blood) is considered incompressible and Newtonian.
- Lagrangian approach is applied to plot the trajectories of some tracer particles of RBCs in the flow to understand the distribution of RBCs along the aortic valve during opening phase (Fig. 6).
- Governing equations are Navier-Stokes equations (a, b) and moving equations of the leaflets (c):

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{u}) = -\nabla p + \frac{1}{Re}\nabla^2 \boldsymbol{u} + \boldsymbol{f}, \qquad \text{(a)}$$

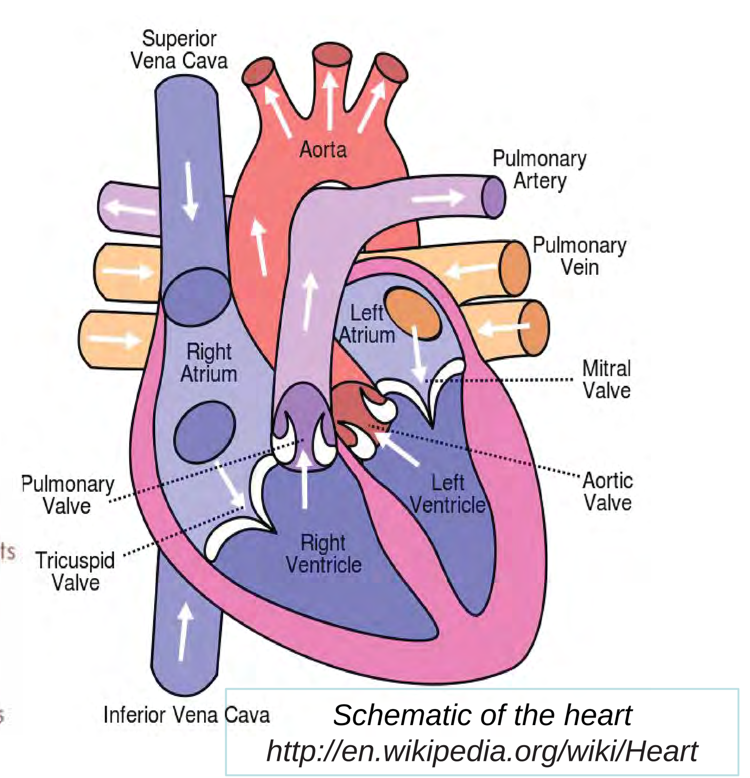
$$\nabla \cdot \boldsymbol{u} = 0, \qquad \text{on } \Gamma \qquad \text{(b)}$$

$$I_i \frac{\mathrm{d}^2\theta_i}{\mathrm{d}t^2} = T_i, \qquad M_i \frac{\mathrm{d}^2 z_i}{\mathrm{d}t^2} = F_i \qquad \text{for } B_i \quad \text{with} \quad i = 1, 2. \qquad \text{(c)}$$

$\boldsymbol{u}$	Velocity vector
p	Pressure
$\boldsymbol{f}$	Direct forcing of immersed boundary method
I_i	Moments of inertia
T_i	Tilting moments

Flow parameters	
Inflow diameter	*d = 25 mm*
Outflow diameter	*D = 28 mm*
Bulk velocity at the peak inflow	$U = 0.81\ m.s^{-1}$
Blood kinematic viscosity	$\nu = 3.04 \times 10^{-6}\ m^2s^{-1}$
Reynolds number	Re = 7200
Density of the leaflets	$\rho_{leaflet} = 2000\ kg/m^3$
Density of fluid (blood)	$\rho_b = 1060\ kg/m^3$
Cardiac output	$5\ l.min^{-1}$

Fig. 1



Schematic of the heart
http://en.wikipedia.org/wiki/Heart

Fig. 2

Results

St. Jude bileaflet mechanical vavle

(1) Opening phase
(2) Peak flow rate (peak systole)
(3) Deceleration phase (diastole)
(4) Closing phase

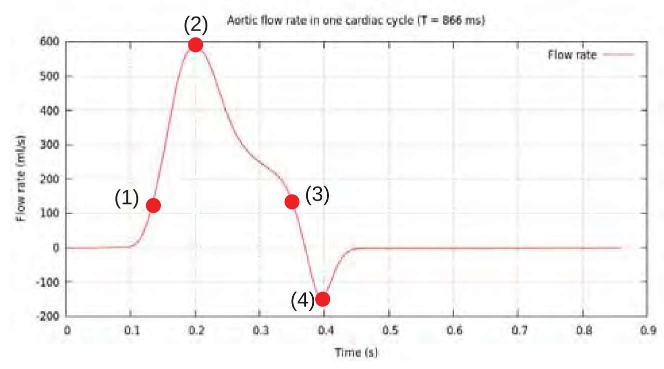
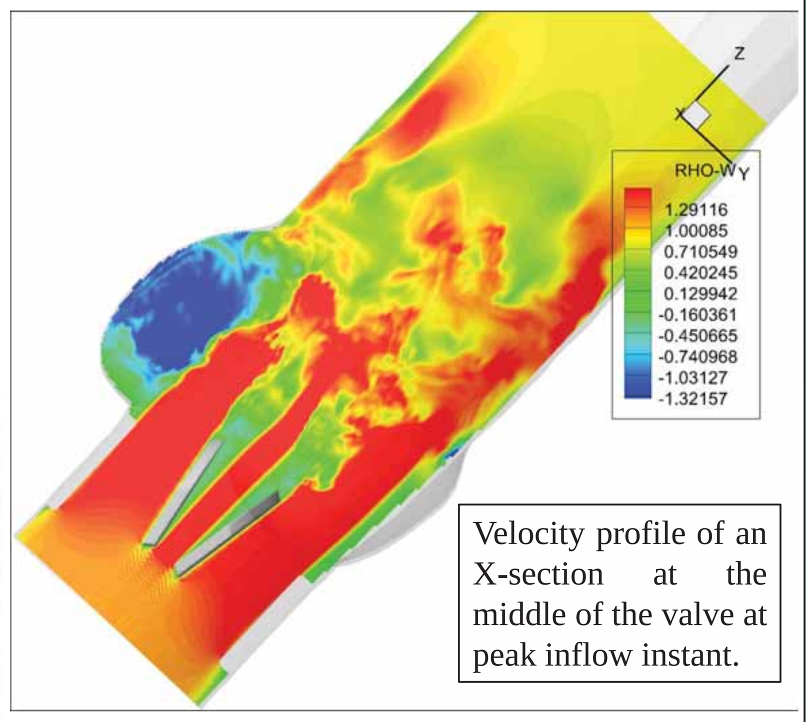


Fig. 3



Velocity profile of an X-section at the middle of the valve at peak inflow instant.

Fig. 4

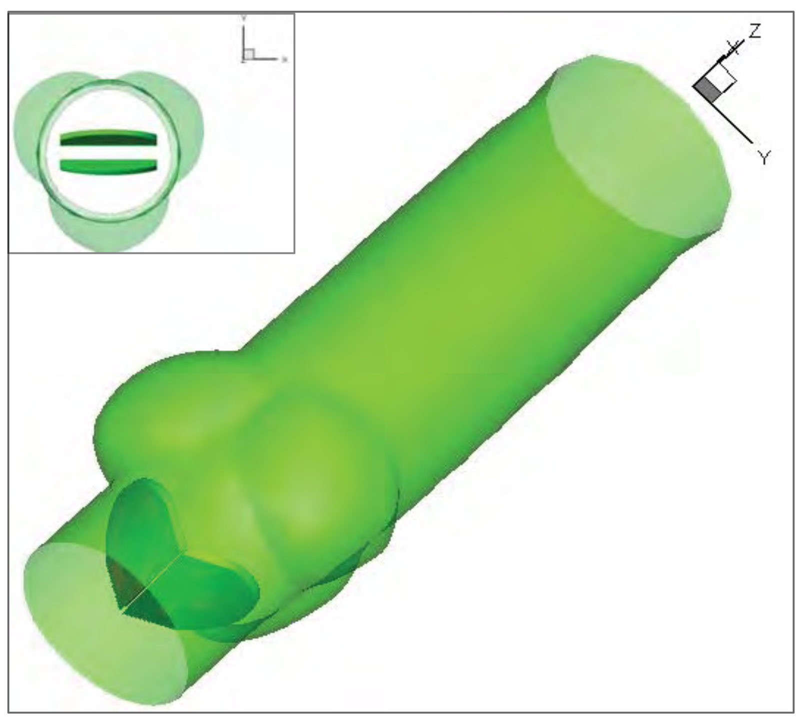


Fig. 5

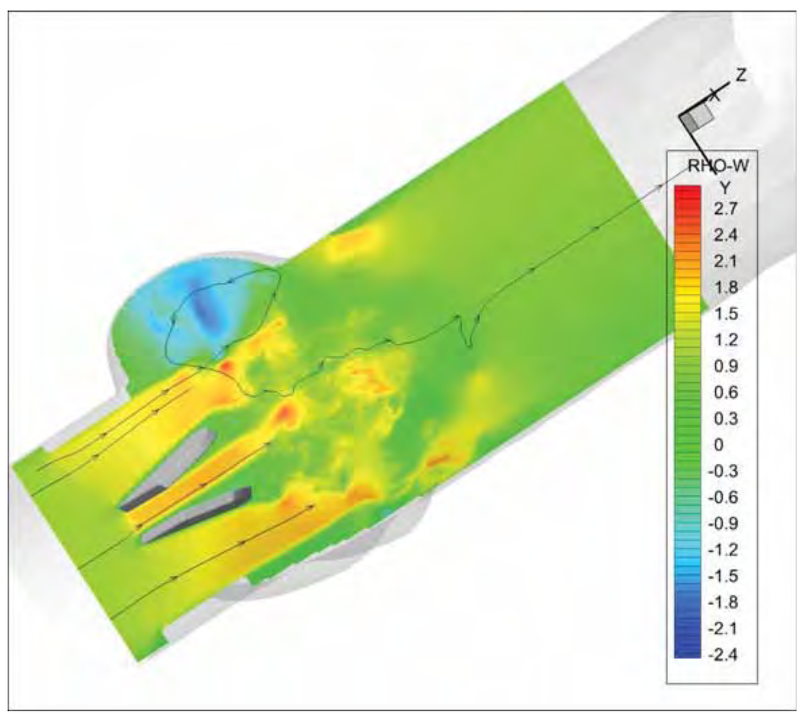
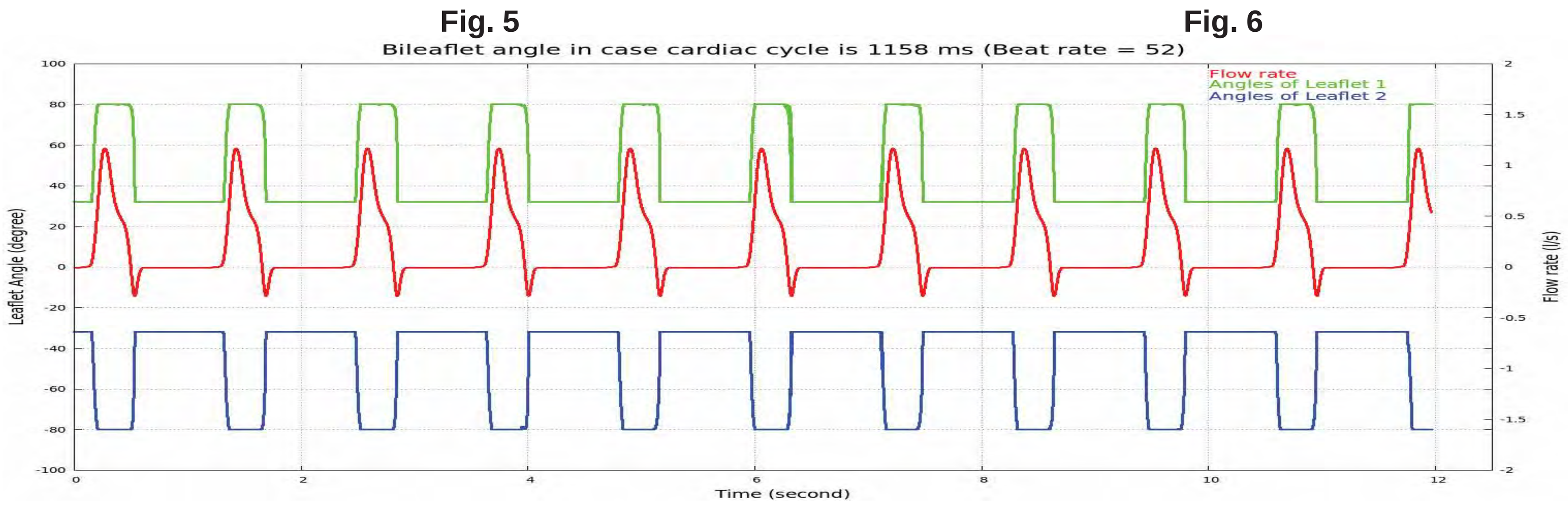
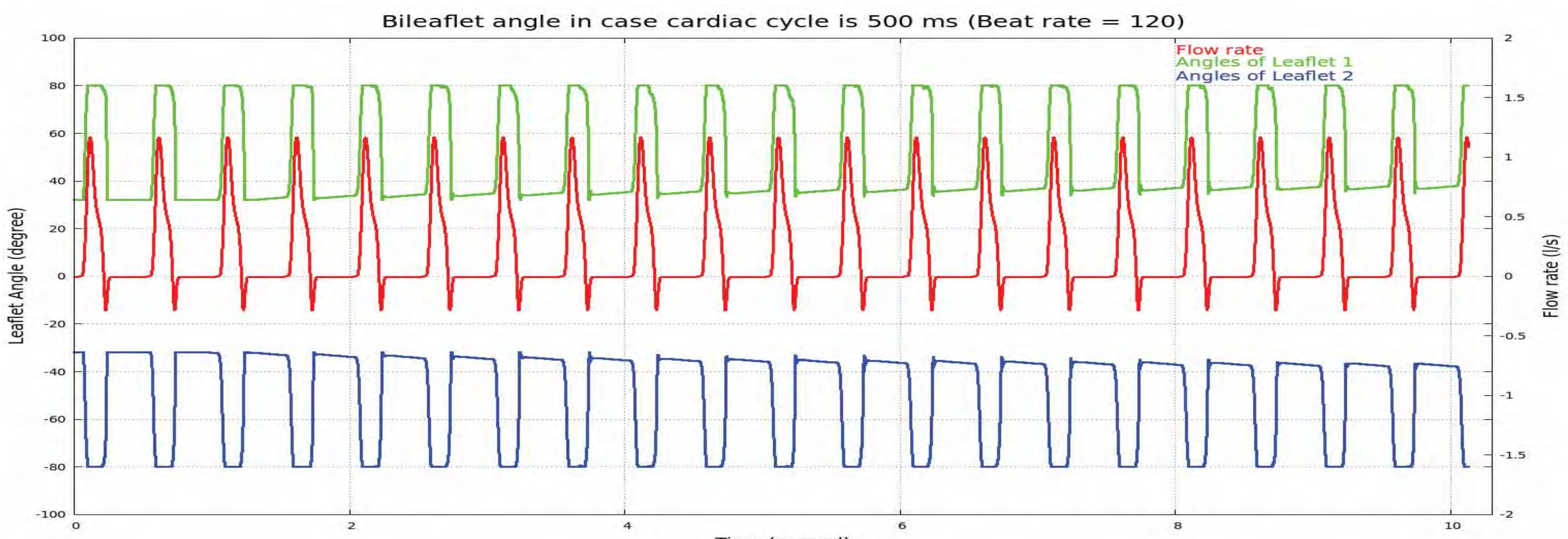


Fig. 6





Conclusions

• Pulsatile cardiac cycle strongly affects dynamics of the bileaflet heart valves. When the cardiac cycle is short (T = 500 ms), motion of leaflets becomes unstable (fluctuates in the closing phase and does not close completely) after only few cycles. If cardiac cycle lasts long, the leaflet seems moving smoothly and stably even after a long time (~ 10 cycles, etc. 10 seconds).
• Turbulent structure of the fluid flow in the opening phase and acceleration systolic phase were plotted give us a visualization of the flow passed over the valves which help us to evaluate effects of the whole flows to the valves (evaluate effects of stresses).

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