COMPUTATIONAL ANALYSIS OF FLUID STRUCTURE INTERACTION IN ARTIFICIAL HEART VALVES

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ABSTRACT

This study presents numerical simulations of a minimum constrained mechanical valve using fully coupled fluid structure interaction (FSI) of COMSOL Multiphysics, a finite element based software. The present model applies a physiological pulsatile pressure gradient across the valve with an approximate symmetric aortic root. The complex hinge from the exact model is simplified with a pin joint with weak constrains to control the fully opened and closed position of the valve. The Arbitrary Lagrangian-Eulerian method is applied in order to accommodate the large mesh displacement due to leaflet motion. Constant material properties are applied to both fluid and structure with the assumption that the flow is Newtonian and turbulent. Overall, the valve leaflet positions and flow patterns are verified against results from literature. Simulations on mechanical valve malfunction identify the generation of vortices, which may suggest regions of high and low velocity for further evaluation.

INTRODUCTION

With the increasing computing power from advancing computer processors and related equipment, the potential to simulate complex physics interaction has been investigating by many research groups[1]-[3]. Dasi et. al, conducted a 3D direct numerical simulation to study pulsatile turbulent flow of bileaflet mechanical valve with particle image velocimetry validation. However, their mechanical valve leaflet motion was determined by probability density function analyzed from experiment. Redaelli et. al, performed a 3D simulation with FSI approach also for bileaflet mechanical valve; however, in order to simulate a laminar flow, the inlet boundary was limited such that the Reynold's number was roughly about 2,400. Another study conducted by Nobili et. al, simulated a 3D bileaflet mechanical valve using direct numerical simulation coupled with FSI. In their study, however, Kolmogorov's scale was not resolved, the motion of the leaflet was purely based on mesh distortion and the stress within the mechanical valve leaflet was not considered. Therefore, the focus of this study was to simulate the interaction between blood hemodynamics and the dynamics of artificial heart valve with fully coupled fluid structure interaction (FSI) method.

The goal of this study is to develop a generalized modeling scheme without increasing artificial constrains or assumptions in order to capture not only the leaflet dynamics but also the stress within the leaflet under pulsatile turbulent flow. With minimum artificial constrain imposed to the model, the freedom to investigate clinically related problems or valve malfunction, such as leaflet arrest, thrombosis, or pannus growth, could be increased. In addition, a simulation has been conducted in order to investigate the flow patterns due to mechanical valve leaflet malfunction.

MATERIALS AND METHOD

Numerical Method

The advantage of the fully coupled FSI method used is that relevant physical parameters, such as wall shear stress and leaflet deformation, could be evaluated during simulation with additional computational resource. COMSOL Multiphysics was chosen since both fluid and structure domain can be fully coupled using finite element method with the flexibility of simulating additional physics with FSI without extensive modifications. Combined with FSI, moving mesh approach is integrated using Arbitrary-Lagrangian-Eulerian (ALE) method with automatic re-mesh to maintain high mesh quality for solution accuracy. The coupling between fluid and structure domain is achieved by transferring boundary velocity and stress between the fluid-structure boundary, shown in Eq1 and Eq2. Mesh independence study is also conducted and found no significant difference between a coarser mesh and mesh for the presented result.

$$u_{fluid} = u_{solid} \tag{1}$$

$$\left[-p\boldsymbol{I} + \mu\left(\nabla\boldsymbol{u}_{fluid} + \left(\nabla\boldsymbol{u}_{fluid}\right)^T\right)\right]\cdot\boldsymbol{n} = \sigma\cdot\boldsymbol{n} \tag{2}$$

where u represents velocity for fluid or solid domain and p, μ, and σ for fluid pressure, viscosity, and solid stress respectively.

Geometrical Models

The geometrical model used in this study is a simplified 25 mm St. Jude Medical bileaflet mechanical valve presented by Choi[4]. The computational domain is shown in Figure 1 with symmetric realistic aorta root implemented. The leaflet length is 12.8 mm with a thickness of 0.65 mm and a free angle of rotation from 25^{o} to 85^{o}. A 3 mm distance separates the simplified pin joints away from one to another.

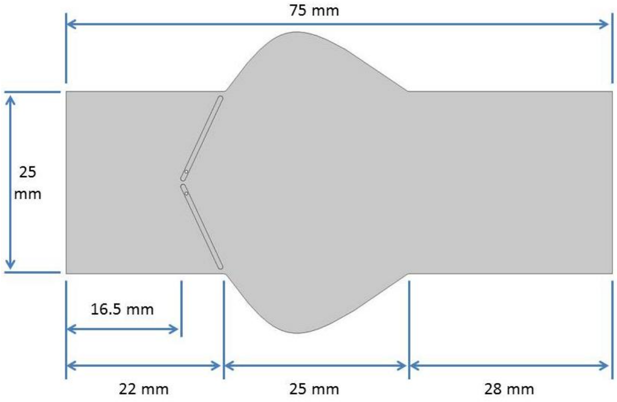


Figure 1: Illustration of the Computational Domain

Simulating Conditions

Table 1: Summary of Material Properties

Properties	**Value**	**Unit**
$Density:\ \rho_{blood}$	1060	kg/m^3
$Viscosity:\ \mu_{blood}$	3.5	cP
$Density:\ \rho_{valve}$	2116	kg/m^3
$Young's\ Modulus:\ E_{valve}$	$30.5\text{x}\ 10^9$	N/m^2
$Poisson's\ Ratio:\ v_{valve}$	0.3	

Table 1 summarizes the parameters that characterize material properties for both fluid and structure domain. As for the model of the artificial heart valve, valve leaflet is assumed to be isotropic, linear elastic material and blood flow is assumed to be isothermal, unsteady, incompressible, and Newtonian.

The imposed inlet and outlet boundaries are governed by physiological pressure profile, which was approximated with Fourier series, shown in Figure 2.

Moreover, due to the physiological pressure gradient imposed to flow boundaries, flow is observed to enter transition region and create difficulty for solver convergence; hence, the two-equation, k-ω turbulent model is incorporated.

Rigid wall assumption is applied to all wall boundaries for blood vessel with no slip condition. The boundaries between fluid and structure domain are defined with FSI boundary condition. As for the valve joints, a free rotation condition is applied with an angular difference counter reaction, only when the valve leaflet reached fully opened or closed position. Since no geometrical constrain is introduced, the complexity of the model is reduced. Zero initial velocity and pressure are applied as initial conditions with simulation started at 0.14 s, shifting away from large pressure difference at t=0 s.

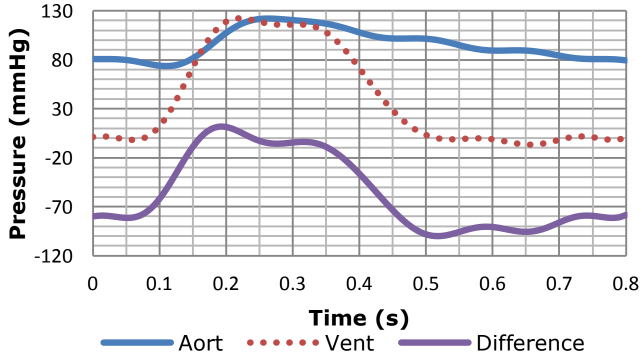


Figure 2: Pressure Profiles for Boundaries

RESULTS AND DISCUSSION

Leaflet Dynamics

The leaflet dynamics for one cardiac cycle is shown in Figure 3a. The approximate duration for both leaflets to reach fully opened position is equal to 70 ms at time equals to 0.23 s, with a fully opened duration of 90 ms until 0.32s. The duration of leaflet closing is 40ms with leaflet fully closed at 0.36 s Rebound, shown in Figure 3b, occurred after both leaflets reached fully closed position and a reaction time of 6ms is taken for leaflet position to reach a steady closing position of 25 degrees.

The leaflet position overshoot due to backpressure from aorta, shown in Figure 3b, causes the leaflet to decrease beyond the minimum angle of 25°. A constant adjusting reaction time for the rebound period is used to characterize leaflet motion such that the counter reaction can be applied precisely. Overall, valve leaflet dynamics is in a good agreement with the results presented by Choi[4] and Guivier[5].

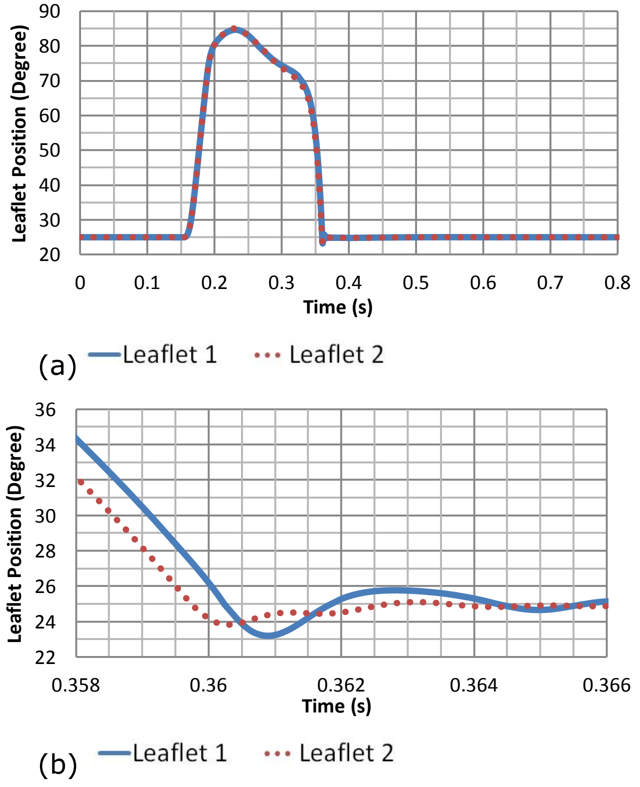


Figure 3: Leaflet Position (a) for one Cardiac Cycle; (b) Near Fully Closed Region

Leaflet Stress

The maximum von Mises stress is calculated for each valve leaflet and is plotted in a semi-log plot, shown in Figure 4, for opening to fully closed phase. During valve opening to closing phase, the maximum stress is maintained well below 0.1 MPa; however, a peak value of 37.6 MPa of maximum stress is calculated during the first rebound period when leaflets reached fully closed position at t=0.361 s. Since the yield strength of the material is approximately 400 MPa, according to the calculated peak von Mises stress, the valve leaflet is safe from yielding.

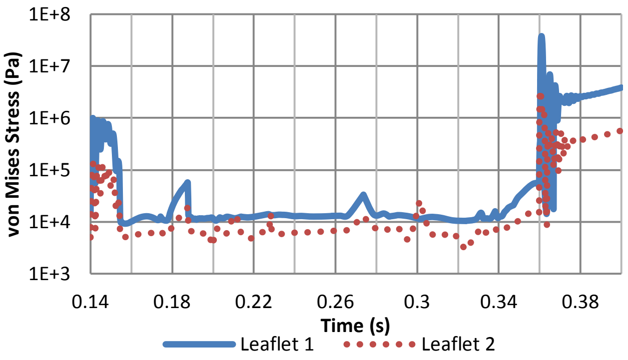
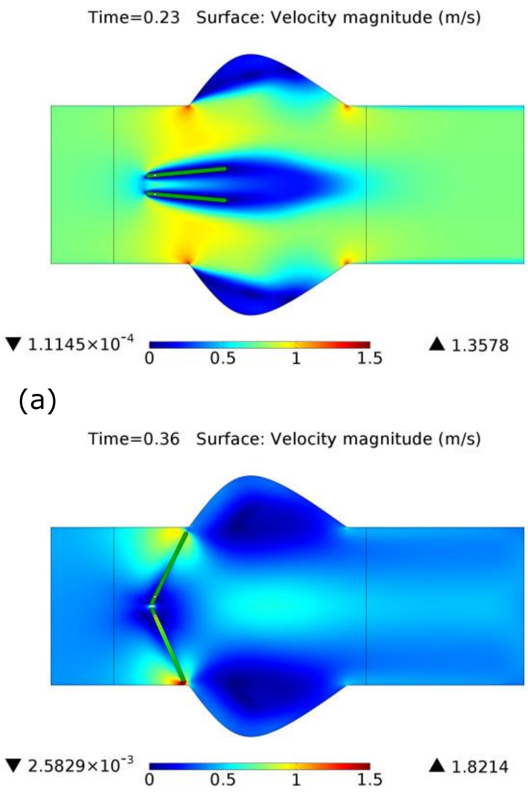


Figure 4: Maximum von Mises Stress in Time

Hemodynamics

The hemodynamics of the artificial valve is presented with isolated time frames, shown in figure 5a and 5b: fully opened (t=0.23), and fully closed (t=0.36), respectively. The effects on the tuning parameters, such as turbulent length scale, for turbulent model are currently under investigation. Symmetric aortic root geometry was assumed for comparing simulated result with future experiments.

To extent this study further, additional simulation is conducted to investigate mechanical valve malfunction, shown in Figure 6. With one leaflet totally constrained to model mechanical valve malfunction, the simulation has successfully identified vortices generate during systolic phase, which may lead to diagnostic complication. The simulation also identifies a high velocity jet passing through the normal leaflet, which could potentially create difficulty of accurately measuring blood pressure gradient during cardiac catheterization. Moreover, comparing the maximum velocity of the normal and the malfunction valve, shown in Figure 5a and Figure 6, the maximum velocity is as much as 25% higher in the case of malfunction valve.



(a)

(b)

Figure 5: Velocity Contour at (a) Fully Opened Position; (b) Fully Closed Position

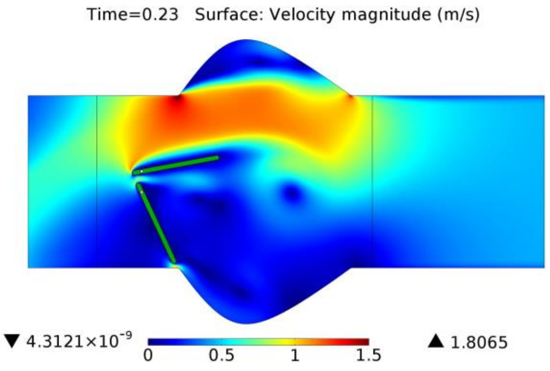


Figure 6: Velocity Contour at Fully Opened Position with One Leaflet Malfunction

CONCLUSION

The presented model has demonstrated an accurate prediction of leaflet dynamics compared against literature with the additional information of leaflet stress evaluated. The computed stress can be used for further investigation on artificial valve damage due to leaflet motion for either mechanical or bioprothetics valve. Additional simulations on mechanical valve malfunction have identified the generation of vortices, which may suggest regions of high and low velocity for further evaluation. Furthermore, the counter reaction has constrained the position of the valve leaflet accordingly with the reduction of geometrical complexity. Nevertheless, the fully coupled FSI simulation with a realistic aortic root has provided additional information on hemodynamics and valve leaflet dynamics for future work on 3D FSI model.

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