11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20 - 25, 2014, Barcelona, Spain

IMAGE-GUIDED FLUID-STRUCTURE INTERACTION SIMULATIONS OF HEART VALVE PROSTHESIS

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Key Words: *Fluid-structure interaction, Immersed Boundary Method, Thin Shells.*

INTRODUCTION

In spite of significant recent advances in imaging modalities for studying cardiac hemodynamics, present day in vivo measurement techniques can only resolve large scale blood flow features. Understanding flow patterns in the heart at physiological conditions and scales sufficiently fine for establishing quantitatively links between disease and patient-specific hemodynamics continues to remain a major research challenge. For instance, in vitro experiments and FSI computational studies have clearly shown that at physiological conditions the presence of a prosthetic heart valve gives rise to complex flow patterns characterized by fine scale flow structures and transition to turbulence. This complex and dynamically rich flow environment is widely believed to be a major culprit for the clinical complications that arise following implantation of valve prosthesis. High-resolution numerical simulation appears to be the only viable option for advancing our understanding of cardiac hemodynamics especially in the presence of prosthetic heart valves.

METHOD OF SOLUTION

We develop a patient-specific model of the left ventricle consisting of: (1) magnetic-resonance images (MRI) data for wall geometry and kinematics reconstruction of the left ventricle during one cardiac cycle; (2) an elastic tri-leaflet aortic heart valve implanted in (3) a realistic aorta interacting with blood flow driven by the pulsating left ventricle. Blood flow is simulated via a new fluid-structure interaction (FSI) method, which couples the sharp-interface CURVIB L. Ge, F. Sotiropoulos [1] for handling complex moving boundaries with a new, rotation-free finite-element (FE) formulation for simulating large structural/tissue deformations described by nonlinear Kirckhhoff thin shells theory H. Stolarski et al. [2].

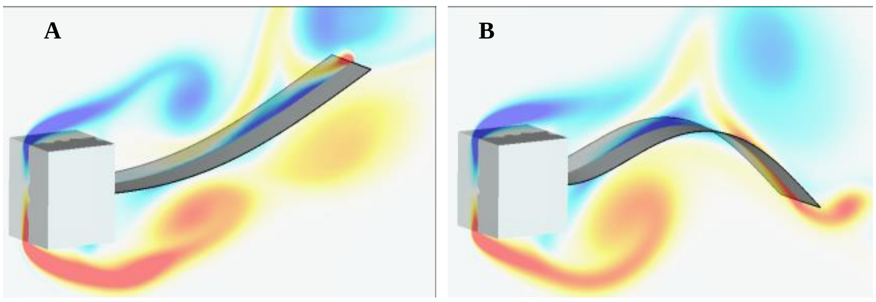

Figure 1. Vortex-induced vibrations of a cantilever in the wake of a square cylinder, simulated with the new version of FSI-CURVIB. (A) is the first and (B) is the second modes of cantilever vibration.

RESULTS

Fig. 1 shows representative results from an application of the new version of FSI-CURVIB to simulate vibrations of a cantilever excited by vortex shedding in the wake of a square cylinder. By changing the cantilever material's density and the flow's Reynolds number (to modify the vortex shedding frequency), our new FSI-CURVIB algorithm can excite both the first and second modes of cantilever vibration, giving results in good quantitative agreement with previously published data [3]. The new version of FSI-CURVIB has been applied to carry out a high-fidelity FSI Direct Numerical Simulation of a tissue valve in an anatomic aorta at physiologic conditions. These results are shown in Fig. 2. The aorta domain was discretized with 2 million nodes and the left ventricle domain was discretized with 1 million nodes, the cardiac cycle was divided in 3000 time steps, and the peak systole Reynolds number is 5900. The valve tissue was modeled as neo-Hookean material with thickness h = 0.6 mm, specific weight of ρ= 1050 kg/m^3, and Young modulus of E=0.5 Mpa. Strong coupling FSI with Aitken relaxation [4] was used as the FSI iteration scheme, requiring 7 to 10 iterations for convergence to a tolerance level of 10^{-5}. Fig. 2 shows instantaneous snapshots of vortical structures visualized by the Q-criterion [5] in the leaflets' wake, illustrating the simulation's ability to capture the onset of the rich turbulent-like state that emerges near peak systole. To our knowledge this is the first report of a coupled 3D FSI simulation of a tissue valve that is able to resolve these complex flow patterns at physiologic conditions and in anatomic aorta geometry.

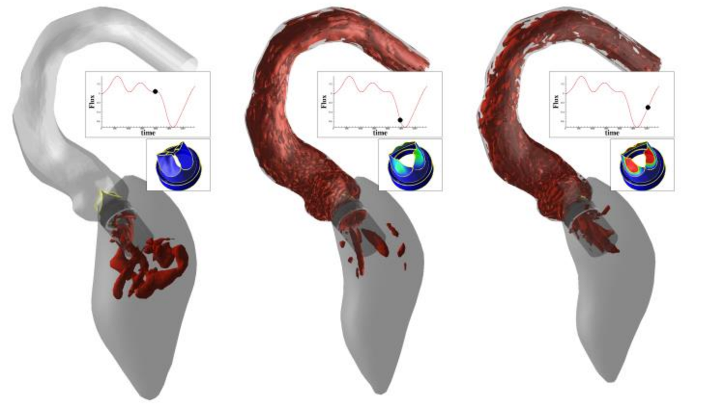

Figure 2. Direct numerical simulation of FSI of a tissue valve in an anatomic aorta using the new version of FSI-CURVIB. Vortical structures are visualized with Q-iso-surfaces [5]. Contours on the valve are magnitudes of velocities. Early, peak and end of systole are shown.

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