A Multiscale/Multiphysics Coupling Framework for Heart Valve Damage

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Abstract: Bioprosthetic heart valves (BHVs) are the most popular artificial replacements for diseased valves that mimic the structure of native valves. However, the life span of BHVs remains limited to 10-15 years, and the mechanisms that underlie BHVs failure remain poorly understood. Therefore, developing a unifying mathematical framework which captures material damage phenomena in the fluid-structure interaction environment would be extremely valuable for studying BHVs failure. Specifically, in this framework the computational domain is composed of three subregions: the fluid (blood), the fracture structure (damaged BHVs) modeled by the recently developed peridynamic theory, and the undamaged thin structure (undamaged BHVs). These three subregions are numerically coupled to each other with proper interface boundary conditions.

In this talk, I will introduce two coupling problems and the corresponding numerical methods we have developed for this multiscale/multiphysics framework. In the first problem the coupling strategy for fluid and thin structure is investigated. This problem presents unique challenge due to the large deformation of BHV leaflets, which causes dramatic changes in the fluid subdomain geometry and difficulties on the traditional conforming coupling methods. To overcome the challenge, the immersogemetric method was developed where the fluid and thin structure are discretized separately and coupled through penalty forces. To ensure the capability of the developed method in modeling BHVs, we have verified and validated this method. In the second coupling problem, we developed a concurrent coupling strategy for peridynamic theory and the corresponding classical elastic theory. In this coupling method, the peridynamic model and the elastic model are solved with a partitioned approach, and the two solvers communicate by exchanging proper boundary conditions at the peridynamics-classical theory interface. We have investigated different coupling scenarios, and analyzed all these scenarios on simplified problems to obtain explicit expressions for the optimal reduction factor (convergence rate index). The analysis suggests that the Robin boundary condition with optimal coefficient would be the most efficient choice. Numerical experiments verified the robustness of the theoretical optimal coefficients, and indicated that the results of the model problem analysis can be extrapolated to the setting of more complicated damage problems.

Biography: Dr. Yue Yu is an Assistant Professor of Applied Mathematics at Lehigh University, where her work focuses on computational multiphysics/multiscale problems. She received her B.S. (2008) degree in Mathematics from Peking University. She earned her M.S. (2013) degree in Mechanical Engineering and her Ph.D. (2014) degree in Applied Mathematics from Brown University. She was a postdoctoral fellow at the School of Engineering and Applied Sciences, Harvard University before she joined Lehigh University in Fall 2014. She is a Committee member of the FSI Technical Trust Area of the United States Association for Computational Mechanics (USACM). She was the recipient of the 2014 Dunmu Ji Thesis Award from Brown University, and she holds a 2018 National Science Foundation CAREER Award.