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SIMULATION AND OPTIMIZATION OF A PULSATILE VENTRICULAR ASSIST DEVICE USING ISOGEOMETRIC ANALYSIS AND FLUID–STRUCTURE INTERACTION

Christopher C. Long[1]*, Yuri Bazilevs,[2] and Alison L. Marsden[3]

[1] Los Alamos National Laboratory T-3, MS B-216, P.O. Box 1663, Los Alamos, NM 87545, cclong@lanl.gov

[2] Structural Engineering, University of California San Diego, 9500 Gilman Dr., La Jolla, CA, 92093-0411

[3] Mechanical and Aerospace Engineering, University of California San Diego, 9500 Gilman Dr., La Jolla, CA, 92093-0411

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A Pulsatile VAD is a medical device which operates as a displacement pump. The basic layout is seen in Fig. 1. The air chamber is pressurized cyclically, which drives membrane motion. The blood chamber then pumps to the patient circulatory system. The membrane buckles non-linearly, making coupled computations difficult. For this work, we utilize a traditional Finite Element approach with VMS–based stabilization [1] on the fluid domains. An Arbitrary Lagrangian–Eulerian method is used to capture the moving domain. We integrate in time using a generalized-α approach, and solve the linear system using a Generalized Minimum Residual (GMRES) method. This approach follows our work in modeling hemodynamics in patient–specific Fontan conduits. [2]

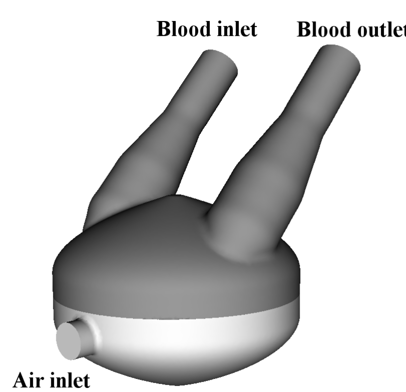

Figure 1: The computational domain, with inlet and outlets of the air and blood chambers labeled.

A Kirchhoff–Love shell model is used on the structural domain. This domain is created using Non-Uniform Rational B-Splines (NURBS), and we perform Isogeometric Analysis (IGA) to solve the structural mechanics. [3] This higher-order approach gives the benefit of smooth, C^1 continuous solutions for the structural deformation, which is key to capturing complex buckling in an efficient way. It also improves the quality of the fluid meshes near the boundary, minimizing “kinks.” However, fundamentally different discretizations and shape functions make coupling with the fluid meshes difficult.

The fully coupled FSI formulation may be written as follows:

$$\mathbf{N}_1\ (\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3) = \mathbf{0}, \tag{1}$$

$$\mathbf{N}_2\ (\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3) = \mathbf{0}, \tag{2}$$

$$\mathbf{N}_3\ (\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3) = \mathbf{0}, \tag{3}$$

where $\mathbf{N}_1$, $\mathbf{N}_2$, and $\mathbf{N}_3$ are the discrete residual functions, and $\mathbf{d}_1$, $\mathbf{d}_2$, and $\mathbf{d}_3$ are the vectors of nodal unknowns, corresponding to the fluid mechanics, structural mechanics, and mesh problems. We employ a "quasi-direct" technique [4], wherein the fluid and structure are solved monolithically, and the mesh is updated block–iteratively.

As mentioned, special techniques are necessary to communicate data across domain boundaries. These methods are presented in detail, along with methods for the quantification of thrombotic risk based on numerical results of particle residence time [5], and the preservation of mesh quality. The PVAD design is parameterized into several key design features, such as chamber radius R and chamber height h. A design space optimization using a surrogate management framework (SMF) [6] is used to find a new PVAD design. This optimization works to minimize the computed thrombotic risk associated with the device, using our particle residence time computations as a cost function. Optimization methods and results are presented in detail, and our future work will be discussed.

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