# A NEW STABILIZED FLUID–STRUCTURE INTERACTION METHOD: COUPLED SYSTEM OF ANISOTROPIC VISCOELASTIC MODEL FOR ARTERY AND NON-NEWTONIAN MODEL FOR BLOOD

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## EXECUTIVE SUMMARY

Fluid–structure interaction (FSI) is a class of multiphysics problems that combines fluids and solids in a single-pass simulation to capture the interactive and integrated behavior of the system. Because of the instabilities that are unique to nonlinear material models, especially in the presence of moving interfaces, a comprehensive strategy for FSI requires mathematical formulations with enhanced stability properties and coupled solution algorithms that preserve the dissipative structure of the underlying coupled continuum problem.

The research team has developed a stabilized monolithic method for coupling incompressible non-Newtonian fluids [1,3,4] with anisotropic (having a physical property that has a different value when measured in different directions) viscoelastic (materials that exhibit both viscous and elastic characteristics when undergoing deformation) models of artery walls. The method is applied to an idealized curved artery to investigate the mathematical attributes of the models as well as that of the coupled solution algorithm. The algorithm and code have been optimized on the XE nodes of Blue Waters.

## RESEARCH CHALLENGE

Realistic, patient-specific models help not only to simulate preoperative diseased configurations but also to analyze postoperative outcomes. This has evolved into the concept of computational medicine, a form of personalized medicine in which patient-specific computer modeling and engineering analysis methodologies are used to noninvasively diagnose and evaluate the efficacy of various possible treatments and to plan and design the optimal intervention based on prediction of outcomes. However, creating spatial discretizations for FSI problems that satisfy nodal compatibility is not always an easy task and, therefore, considerable effort has been devoted to numerical methods that accommodate nonmatching interfaces [2]. Flexibility to accommodate nonmatching meshes is of great practical value in problems of industrial strength that invariably have complex geometric configurations. Relaxing the nodal continuity requirements necessitates techniques for enforcing the conditions on the continuity of the fields across the interface. The research team followed the ideas proposed in Truster and Masud [5,7] and developed an interface-stabilized method with least-squares-type terms that enforce continuity of traction at the nonmatching meshes along the fluid–solid interface.

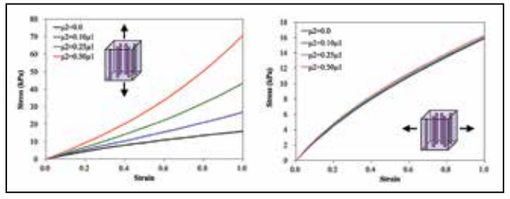

Figure 1: Anisotropic tissue/collagen-fiber model for the artery wall.

Accurate prediction of stress and deformation in the arterial wall in patient-specific applications requires that physiologically relevant constitutive models [6] are employed for the artery wall, which is comprised of soft tissue with embedded collagen fibers. Anisotropy caused by embedded fibers in soft biological tissues is a more difficult numerical problem, and it becomes a challenge for numerical methods when large deformations are involved in an FSI simulation. In the present work, multiple layers of artery wall, intima (the innermost layer of an artery or vein), media, and adventitia (the outermost layer of the wall of a blood vessel) are modeled via a hyperelastic energy functional that accounts for finite stretching of the soft tissue as well as anisotropy induced by the directionally oriented collagen fibers. The reinforcing fibers are laid helically around the artery wall with alternate layers placed orthogonally to one another to form a network of directionally oriented layers.

$$W(\boldsymbol{C}) = \varepsilon_1\left(I_3^{\varepsilon_2} + I_3^{-\varepsilon_2} - 2\right) + c_1\left(I_1 I_3^{-1/3} - 3\right) + \sum_{\alpha=1}^{2} \alpha_1 \left\langle I_4 J_4^{(\alpha)} - J_5^{(\alpha)} - 2\right\rangle^{\alpha_2}$$

where $I_1$=trC, $I_3$=detC, $J_4$=tr[CM], and $J_5$=tr[C²M] are invariants of the right Cauchy–Green deformation tensor; M=a⊗a is a second-order tensor that models anisotropy of the fibrous material with a direction vector a; $\varepsilon_1$, $\varepsilon_2$ and $c_1$ are the material parameters for a neo-Hookean type solid; and $\alpha_1$ and $\alpha_2$ are material parameters for reinforcing fibers.

## METHODS & CODES

Numerical methods, which are not constrained by node-on-node matching, provide great advantage in developing patient-specific computational models. The researchers have employed a variational multiscale framework to develop advanced numerical techniques with enhanced stability and accuracy properties for this class of problems. The team's emphasis has been on the development of a unified mathematical framework that can have wider application both in the domain of fluids as well as in solids. The enhanced stability facilitated by the mathematical constructs results in a robust FSI algorithm that has been applied to the blood–artery interaction problem. The method is implemented in the context of a finite-element method using low-order Lagrangian elements and has been optimized on the XE nodes of Blue Waters.

## RESULTS & IMPACT

Fig. 1 shows the stress-strain response for a representative material volume of the artery wall to illustrate its anisotropic response under axial stretching. A parametric study was carried out with biologically relevant values of the material coefficients, and the nonlinear stress-strain response is presented in Fig 1. The sample was first loaded in the axial direction that is aligned with the direction of the fibers and a gradual stiffening response was observed. Subsequently, the unit cube was loaded in the lateral direction and the stress-carrying capacity was reduced by five times. In addition, a gradual softening response was observed, as shown in Fig. 1b.

Fig. 2 shows the curved geometric configuration of the blood–artery model. The unidirectional collagen model was put in layers to create a network that is shown by the red and blue fibers in Fig. 2a. The mesh was comprised of hexahedral elements where the red region represents the fluid subdomain. The researchers simulated a few cardiac cycles and Fig. 2c presents an instantaneous snapshot of the deformation of the artery wall along with the streamlines of the blood flow. The team also projected the arterial wall shear stress (WSS) on the artery wall, which is one of the most significant factors affecting the progression of arterial disease. Since it is difficult to obtain spatiotemporal WSS data via *in vivo* experiments, advanced FSI simulations with appropriate constitutive models provide a virtual platform to facilitate important and insightful information for the diagnosis and treatment of arterial disease. Such information can also be critical at the planning stage for developing patient-specific strategies for surgical intervention.

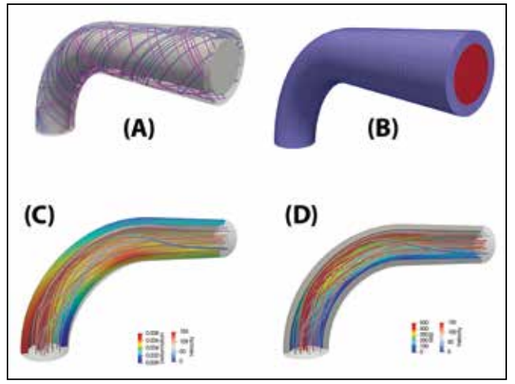


Figure 2: (a) curved artery model reinforced with helically arranged collagen fibers; (b) computational mesh for blood and artery wall; (c) deformation of artery wall with superposed streamlines; (d) wall shear stress and streamlines of blood flow.

## WHY BLUE WATERS

The coupled solution algorithm for nonmatching FSI meshes was implemented on the Blue Waters platform and tested on XE nodes. Since element-level developments are all local to individual elements both in fluids and in solids, this part is easily and efficiently parallelized. However, the interface coupling terms need special attention as they require information from both fluid and solid subdomains across the interface. This implementation takes advantage of the local memory on the processing node, thereby expediting the calculation of element-level matrices and vectors. Preliminary tests confirm the robustness of the method for highly nonlinear problems. This model will now be applied to patient-specific geometry to see the scalability of the FSI method with nonmatching meshes to problems of clinical relevance.

## PUBLICATIONS & DATA SETS

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