Research Statement

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My current research interests are focused at the interface between biology, mathematics, fluid dynamics and numerical methods. More specifically, my research involves modeling, analyzing and simulating the dynamics of domain formation in vesicle biomembranes in a viscous fluid. I have developed efficient and accurate numerical algorithms using a boundary integral approach.

Past work

Numerous experimental, analytical and numerical studies have been performed on vesicle biomembranes. The origins of these studies stem from the desire to explain the biconcave shape of red blood cells. Although the red blood cell represents a highly complex system, many believe that the key to understanding its shape lies in considering a much simpler model such as a vesicle. Closed biomembranes (vesicles) are important class of problems where bending forces play an active and critical role in interface morphology. The basic structural component of all biological membranes are lipid bilayers. In general, however, biomembranes are very complex structures that contain lipids, proteins, cholesterol, ions, etc. Because of their complexity, it is challenging to study all the biophysical effects in biomembranes.

In recent years, it has been increasingly recognized that the presence of different types of lipids in the bilayers can result in the generation of curvature and complex vesicle morphologies which thus has implication of more complex biomembranes.

In my thesis, I have developed a sharp interface model for the dynamics of multicomponent (non-homogeneous) inextensible membranes in a viscous fluid. Most studies of multicomponent vesicles have focused on the determination of equilibrium shapes using sharp interface models [1, 11, 20, 15, 6, 10, 4, 5, 7, 2, 16, 18] and diffuse interface models [3, 23, 14]. Until my work, there have been no studies of the dynamics of multicomponent vesicles in a viscous fluid (their natural medium). This is a very difficult problem as it involves a highly nonlinear, nonlocal evolution problem in which phase transformations occur on the surface of the deforming vesicle, creating domains rich in one lipid type and poor in the other. These phases can have different bending stiffness and spontaneous (preferred) curvatures. In addition, the vesicle is inextensible and this is accounted for by a Lagrange multiplier (tension) that introduces the force in the fluid necessary to maintain inextensibility.

There have been only a few studies using sharp interface models of inextensible homogeneous vesicles in a viscous fluid [12, 24, 19, 22] because of the difficulties involved in solving the high-order nonlinear systems of equations. The stiffness introduced by bending forces posed a formidable challenge that was only recently overcome in two dimensions by Veerapaneni et al.
[22] who developed a nonstiff algorithm by extracting dominant contributions to the equations at small spatial scales, following Hou et al. [8], Kropinski [13], Tornberg and Shelley [21] and Hou and Shi [9].

I have developed and investigated a thermodynamically consistent model of two-dimensional multicomponent vesicles in an incompressible viscous fluid with my colleagues. The model is derived using an energy variation approach that accounts for variation among the surface phases and the associated the excess energy (line energy) between juxtaposed surface phases, bending energy, spontaneous curvature, local inextensibility and fluid flow via the Stokes equations. In particular, we derived the generalized Laplace - Young boundary condition for the normal stress jump across the vesicle membrane. The equations are high-order (fourth order) nonlinear and nonlocal due to the incompressibility of the fluid and the local inextensibility of the vesicle membrane so that it is highly challenging to perform dynamical simulations of all effects.

To solve the equations numerically, I developed a nonstiff, pseudo-spectral boundary integral method that relies on an analysis of the equations at small scales. The small scale decomposition is used to develop efficient, explicit time integration schemes for both the evolution of the membrane and the surface phases. In addition, the equation for the Lagrange multiplier introduced to enforce local inextensibility is reformulated. This work has resulted in one first author publication [17], with another in preparation. An example simulation of a multicomponent vesicle tumbling in a shear flow is given in Fig.(1)

![Figure 1](image_url)

Figure 1: A multicomponent vesicle tumbling under an applied shear with a 30-70 mixture of lipid phases. The evolution of the vesicle at the indicated times (blue and red correspond to the concentration=0 and concentration=1 phases respectively).
Ongoing work

In ongoing work, I am extending the algorithm to 3D axisymmetric vesicles. To do this, I have also collaborated with Shuwang Li and Xiaofan Li, from IIT in Chicago, IL. I compared our results with experimental vesicle morphologies [2]. By using same parameter settings, we obtain a good agreement between the experimental and theoretical results. A paper describing these results is being prepared for submission.

In the future, I plan to continue working on these and other research problems that involve interesting mathematics and complex fluid dynamics with applications to biology as well as the to physical and engineering sciences. I would like to incorporate additional biophysical effects, such as proteins and cholesterol, into our current algorithm.

As a graduate researcher, I continuously evaluate my research, view it from new perspectives, and challenge myself to improve it where possible. I also maintain an active interest in related research areas, from which I derive a rich supply of ideas and techniques to tackle new problems. By working at the interface between theory and practice, I hope to make unique and lasting contributions at the interface between mathematics, physical and biological sciences.

References


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