Abstract

Fluid-structure interaction has been the subject of extensive study due to its application in numerous fields of scientific and applied research including the motion of micro-organisms, insects, birds, fishes, aircrafts, arterial blood flow, automotive aerodynamics, deflection of wind turbine blades, falling of a leaf, rocking motion of ships, elastic filaments, and flexible polymers in fluid media, to name a few. Broadly, this dissertation considers two topics in the context of fluid-structure interaction. The first part covers the theoretical derivation of a generalized slender body theory for the motion of special Cosserat filaments in Stokes flow. In the second part, an efficient singularity-free numerical technique is proposed to solve the motion of filaments in Stokes flow using the proposed slender body theory and further demonstrate the numerical technique through simple flow problems such as filament motion in background shear and compressional flow, and twirling-overwhirling motion of filament in background static flow.

To study the motion of filaments in fluid media, a well known *slender body theory* exists wherein the fluid flow is assumed to be Stokesian while the filament is modeled as a Kirchhoff rod which can bend and twist but remains inextensible and unshearable. In the present work, the inextensibility and unshearability constraints on filaments are relaxed, i.e., the filament is modeled as a special Cosserat rod. Starting with the boundary integral formulation of Stokes flow involving the filament's surface velocity and fluid traction that acts on the filament surface, the method of matched asymptotic expansion is used to first obtain a leading order representation of the boundary integral kernels in filament's aspect ratio. Thereafter, Fourier series expansion (in filament's circumferential coordinate) of both the filament's surface velocity and fluid traction are substituted in the aforementioned leading order representation. This is further linearized in the rod's shear strains to reduce the two-dimensional boundary integral over the filament surface into a line integral over the filament's centerline. Upon further collecting the coefficients of sine and cosine terms, the zeroth order Fourier mode yields a non-local line integral equation relating the rod's centerline velocity with the distributed fluid force that acts on the filament. The presence of line integral makes the relation non-local in nature. On the other hand, the first order Fourier mode yields a simpler local relation between the rod's angular velocity and the distributed fluid couple. The line integral equation is shown to reduce to the classical slender body theory when the shear strains and the axial strain are set to zero. The non-dimensional governing equations of the special Cosserat rod are also derived accounting for the distributed fluid force and distributed fluid couple in them.

As the derived slender body theory contains singularity, an efficient singularity free numerical scheme is proposed in the present work to solve the governing equations. It has been observed from the literature review that this singularity is tackled using cut-off length, i.e., by removing the portion of singularity from the full domain or using mollifiers such as in the method of regularized stokeslet. In the present work, no cut-off length or mollifier is used to remove this singularity. It is demonstrated that the singularity is of removable type which, once removed, makes the system well defined in the entire domain. A second-order accurate finite-difference method is employed to discretize the governing equations. In addition to bending deformation of the filament, the present formulation also includes stretching, shearing and twisting deformations of the filament which have been largely neglected in existing literature. The numerical scheme is demonstrated through example problems of the filament behaviour in background shear flow wherein the importance of distributed couple term is investigated, background compressional flow wherein an interesting phenomenon of perversion is explored, and filament's twirling - overwhirling transitions when the filament is spun about its own axis in initially static fluid. The comparison between Kirchhoff and special Cosserat based slender body theories is performed in all the examples. It is shown that for relatively shorter filaments where the effect of shear and axial stretch is more dominant, the results obtained from the present work deviate from the ones based on the classical slender body theory.