Abstract

Simulation and Design of Soft Robotic Swimmers with Artificial Muscle

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Soft robots take advantage of rich nonlinear dynamics and large degrees of freedom to perform actions often by novel means beyond the capability of conventional rigid robots. Nevertheless, there are considerable challenges in analysis, design, and optimization of soft robots due to their complex behaviors. This is especially true for soft robotic swimmers whose dynamics are determined by highly nonlinear fluid-structure interactions. We present a holistic computational framework that employs a multi-objective evolutionary method to optimize feedback controllers for maneuvers of a soft robotic fish under artificial muscle actuation.

The resultant fluid-structure interactions are fully solved by using a novel fictitious domain/active strain method, developed to numerically study the swimming motion of thin, lightweight soft robots composed of smart materials that can actively undergo reversible large deformations. We assume the elastic material to be neo-Hookean, and behave like an artificial "muscle" which, when stimulated, generates a principal stretch of contraction. Instead of imposing active stresses, here we adopt an active strain approach to impose contracting strains to drive elastic deformation following a multiplicative decomposition of the deformation gradient tensor. The hydrodynamic coupling between the fluid and the solid is then resolved by using the fictitious domain method where the induced flow field is virtually extended into the solid domain. Pseudo body forces are employed to enforce the
interior fictitious fluid motion to be the same as the structural movement. To demonstrate this method we carry out a series of numerical explorations for soft robotic swimmers of both 2D and 3D geometries that prove these robot prototypes can effectively perform undulatory and jet-propulsion locomotion when active contracting strains are appropriately distributed on elastica.

To complete our framework we then demonstrate the design and optimization of a maneuverable, undulatory, soft robotic fish. In particular, we consider a two-dimensional elastic plate with finite thickness, subjected to active contractile strains on both sides of the body. Compared to the conventional approaches that require specifying the entire-body curvature variation, we demonstrate that imposing contractile active strains locally can produce various swimming gaits, such as forward swimming and turning, using far fewer control parameters. The parameters of a pair of proportional-integral-derivative (PID) controllers, used to control the amplitude and the bias of the active strains, respectively, are optimized for tracking a moving target involving different trajectories and Reynolds numbers, with three objectives, tracking error, cost of transport, and elastic strain energy. The resulting Pareto fronts of the multi-objective optimization problem reveal the correlation and trade-off among the objectives and offer key insight into the design and control of soft swimmers.

Furthermore, rich and complex phenomena occur at the interface between fluids and elastic solids that can influence the behavior of the overall system. This is especially true in the case of soft robots where wrinkling, folding, and similar wavelike behavior can occur at the surface and affect the momentum transfer which is necessary to produce locomotion. To begin to understand this behavior we analytically investigate the linear stability of a viscoelastic gel-like film subjected to Newtonian Couette flow in the limit of vanishing Reynolds number.