Fluid-Structure Interaction Model for Actuation of Immersed Light-Responsive Liquid Crystal Elastomer (LCE) Beams

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Abstract

Liquid Crystal Elastomers (LCEs) are a class of smart materials capable of undergoing large, reversible deformations when exposed to external stimuli such as light, heat, or humidity. Among these stimuli, light is particularly appealing as it enables precise, non-contact control over LCE properties, leading to complex deformations and dynamic behaviors. Recent experimental researches have demonstrated the potential of light-actuated LCE beams immersed in fluid environments. For example, one study reported self-oscillation in a planar LCE beam immersed in water, driven by the self-shadowing effect under constant illumination (1). Another study described a light-powered micro-swimmer inspired by the anatomy and motion of ephyras, composed of four beam and demonstrated its propulsion capabilities (2). The actuation of LCE beams under light involves a complex interplay of multiple physical processes spanning structural mechanics, heat transfer, light absorption, chemical reactions, and, when submerged in a fluid, fluid dynamics. This multi-disciplinary nature makes it essential to understand the underlying physics governing these interactions to enhance the performance and functionality of LCE systems. In particular, the dynamic response of LCEs in fluidic environments, including phenomena such as self-oscillation and light-driven swimming, is an area of growing interest. In this work, we developed a multi-physics fluid-structure interaction model using COMSOL software to investigate the dynamic behavior of LCE beams immersed in a fluid and subjected to light. Our model integrates several phenomena, including nonlinear structural mechanics, fluid mechanics, heat transfer, and chemical reactions, while incorporating the Beer-Lambert law to capture light absorption. Deformations and bending of the LCE beam are driven by either thermal or chemical effects, depending on the specific problem and light stimulus.

Inspired by the experimental study in (1), we applied the model to study the self-oscillation of an immersed LCE beam under steady illumination. Self-oscillation occurs due to a feedback loop driven by the self-shadowing effect, where the beam's deformation alters the light intensity distribution along its surface, causing periodic motion. We conducted a detailed parametric analysis to understand how various factors influence the oscillation behavior, including beam length, and light intensity. The results highlight the impact of these parameters on the amplitude and frequency of oscillation, offering valuable insights for optimizing

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the design and functionality of LCE-based devices.

In addition to investigating self-oscillation, we extended our model to simulate a two-dimensional (2D) light-powered swimmer inspired by the ephyra, as described in (2). In this model, a thin LCE beam is considered as the swimmer, with its propulsion and steering controlled by modulating two light sources with independently adjustable illumination periods. The actuation mechanism relies on the photochemical reactions of azobenzene molecules embedded in the LCE. Specifically, under light exposure, the azobenzene undergoes a trans-to-cis isomerization, causing a localized contraction in the LCE material and bending towards the light source. This deformation drives the actuation of the swimmer. A second light source is used to facilitate relaxation by reversing the isomerization process or redistributing the molecular configuration to allow recovery of the original shape. The interplay between these two light sources creates a dynamic cycle of deformation and relaxation, enabling control of the swimmer's motion. Our simulations explore the impact of this light-modulated actuation-relaxation process on the swimmer's propulsion, stability, and steering. This approach highlights the potential of chemically-driven light-responsive mechanisms for achieving controlled navigation in fluidic environments.

References

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