Nonreciprocal dynamics of active structures

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Abstract

Reciprocity is a property of linear physical systems that manifests through relations of symmetry (e.g. Betti's theorem). This remarkable and fruitful property also imposes strict constraints, escaping which is of interest in science and engineering (1). Working with polyelectrolyte (PE) hydrogels as a prototypical example of artificial active materials, we investigate the complex nonreciprocal behaviours arising from their response to electric stimuli by theoretical, numerical and experimental methods.
The movements of aquatic micro-organisms need to break time-reversal symmetry in order to produce fluid flows and achieve locomotion, as dictated by the constraints of low Reynolds number hydrodynamics. We found that flutter instability can be harnessed to produce self-sustained nonreciprocal oscillations in a PE hydrogel-based soft robot, leading to undulatory swimming under minimal actuation from a steady electric field (2).

The susceptibility of PE hydrogels to environmental stimuli can also be exploited to break spatial symmetry and thus investigate nonreciprocal transmission phenomena both in the static and dynamic regime. In particular, we focus on a periodic structure of PE hydrogel rods, exhibiting nonreciprocal behaviours, that can be predicted with a simple mathematical model. Moreover, the ability of PE hydrogel to harvest energy from the external stimulus allows to overcome viscous damping from the surrounding fluid and eliminate attenuation, leading to unidirectional wave amplification.

While notable examples of these behaviours have been presented in recent literature, our research proposes a different approach where the material itself acts both as actuator and control system. By exploiting the intrinsic response of PE hydrogels to the electrical stimulus, low level control tasks are offloaded to the interaction of the structure with the environment.

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