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Simple stimuli drive complex responses in non-Euclidean active shells

Roberto Marchello[1], Pietro Maria Santucci[2], Giovanni Noselli[3]

[1] SISSA - International School for Advanced Studies, Italy. rmarchel@sissa.it
[2] SISSA - International School for Advanced Studies, Italy. psantucc@sissa.it
[3] SISSA - International School for Advanced Studies, Italy. gnoselli@sissa.it

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Abstract

Synthetic active materials are opening new avenues towards biomimetics in soft robotics. Understanding how active forces and stresses are generated in these smart systems, and how they drive complex behaviours such as deformations, shape changes, and motion, is therefore crucial. In this context, mechanical instabilities arising from the interplay between elasticity, internal active processes and external environmental cues are of central importance. These instabilities not only enrich our understanding of natural systems, but also open paths toward designing new responsive and adaptive materials. This work is motivated by recent experimental observations showing that polyelectrolyte hydrogel filaments undergo self-sustained, large-amplitude oscillations when exposed to a steady, uniform electric field. These nonreciprocal deformations originate from flutter instabilities and allow the filaments to generate thrust or to swim in a viscous environment, mimicking the behaviour of biological cilia and flagella [1,2,3]. Intrigued by these findings, we investigate the complex dynamical behaviours active shells exhibit in response to electrical stimuli through mathematical modelling, numerical simulations, and physical experiments. Such active shells are non-Euclidean, as they lack a stress-free reference state due to geometric incompatibilities induced by internal activity [4,5]. The theoretical framework relies on morphoelasticity, enriching nonlinear Koiter shell theory with an inelastic spherical spontaneous curvature that encodes the material's active response to external stimuli and captures how active forces act on the system. Fluid-structure interactions with the surrounding viscous environment are modelled in the low Reynolds number regime using reduced hydrodynamic theories. Compared to rod-like structures, active shells are found to exhibit a richer behavior at large deformations ensuing from the competition between stretching and bending energies. The mathematical model is specialized to active elliptic plates and cylindrical shells free to move in a viscous environment. We demonstrate the emergence of flutter through a linear stability analysis and predict its dependence upon the model parameters. Our analysis is confirmed by numerical simulations of the nonlinear model and by physical experiments on polyelectrolyte hydrogel elliptic plates under the action of a constant and uniform electric field. Both simulations and experiments agree in showing the achievement of oscillatory nonreciprocal motions of large amplitude. By bridging theory, simulations, and experiments, this work elucidates how smart synthetic structures can advance the understanding of biomimetic locomotion mechanisms and provide insights into the design of soft actuators.

Keywords:

Bioinspired systems Soft active materials Non-Euclidean shells Flutter instability Polyelectrolyte hydrogels

References:

[1] Cicconofri, G., Damioli, V., Noselli, G.,"Nonreciprocal oscillations of polyelectrolyte gelfilaments subject to a steady and uniform electric field",J. Mech. Phys. Solids, 173, 105225 (2023).

[2] Boiardi, A. S., Marchello, R., "Breaking the left-rightsymmetry in fluttering artificial cilia that performnonreciprocal oscillations", Meccanica, 59, 1255–1268(2024).

[3] Boiardi, A. S., Noselli, G., "Minimal actuation andcontrol of a soft hydrogel swimmer from flutterinstability", J. Mech. Phys. Solids, 191, 105753 (2024).

[4] Efrati, E., Sharon, E., Kupferman, R., "Elastic theoryof unconstrained non-Euclidean plates", J. Mech. Phys.Solids, 57-4, 762-775, (2009).

[5] Marchello, R., Santucci, P. M., Noselli, G., "Simplestimuli drive complex responses in non-Euclidean activeshells", in preparation.