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Magnetic-field-actuated beating of magnetoactive cilia for object transportation

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Actuation systems based on smart magnetic materials offer significant advantages in applications where contactless control and minimal interference with biological substances are required. In nature, cilia perform a wide range of vital functions in biological organs, enabled by their capabilities for motility and sensing. Ciliary beating is a complex, optimized motion facilitating the transport of substances such as mucus in the respiratory tract and ova in the reproductive system. One promising approach to realizing artificial magnetic cilia is based on the use of magnetoactive elastomers, which are solid elastomeric composites exhibiting striking magnetic properties due to the incorporation of micron-sized magnetic particles.

In this work, theoretical and experimental studies of the deformation of a MagCilium –a magnetoactive beam inspired by biological motile cilia –are conducted under the combined influence of elasticity, gravity, and a magnetic field. The beating of the MagCilium is generated through a combination of three control parameters: the strength and inclination angle of the applied homogenous magnetic field, as well as the fixation angle at the cilium base. The theoretical analysis of quasi-static two-dimensional deformation is based on a nonlinear bending theory, incorporating a magnetic moment and formulated for beams with conical cross-sections and different initial curvature. Numerical simulations determine the deformed shapes of MagCilia and predict combinations of control parameters at which jump-like changes in the quasi-static shape may occur. The geometric parameters of conical and initially curved MagCilia that maximize the beating pattern are identified. In the experimental study, deformed shapes for five selected MagCilia geometries are observed under variation of two of the three control parameters: the strength of a vertical homogeneous magnetic field and the fixation angle. The experimental results confirm the presence of jump-like shape changes. The deformed MagCilia shapes, identified using image processing techniques, are compared with theoretical shapes, showing good agreement, with the normalized root mean square error for the vast majority of observations remaining below 10%. The findings demonstrate that the integration of multiple artificial MagCilia into a two-dimensional array provides a method for efficient object transport via controlled beating patterns under designed contactless magnetic field actuation.

Type:

Oral