Snap-through instabilities in magneto-elastic slender beams interacting with rigid obstacles.

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Abstract

Permanently magnetizable soft slender structures are employed in remote locomotion of soft robots, catheter tips in the enclosed channels (1), etc.. Recently, the magnetic field-assisted catheter locomotion has gathered immense research focus due to its facile fabrication and low-field remote actuation of ˜ 10 – 50 mT. The catheter locomotion inside enclosed, tortuous channels leads to extreme mechanical deformation and often snapping-type instabilities. This work theoretically investigates the possibility of employing the snapping of pre-magnetized magneto-elastic beams while interacting with rigid surfaces in understanding the surface quality of the obstacle, i.e., the surface roughness and other tribological characteristics. Our analysis shows that the snapping response of the beams under magnetic fields may differ substantially depending on the surface roughness and curvature. Thus, the health of tissues can be monitored in a minimally invasive setting by recording the magnetoelastic snapping signature of a beam against it. This may lead to a protocol for non-invasive tissue health monitoring.

The geometrically exact beam theory is employed to model the planer (2D) motion of flexible magnetoelastic beams. The magnetic body torque-based model can successfully predict the flexural deformation of slender pre-magnetized structures (2). Here we use the magnetic body torque model with the 2D geometrically-exact beam theory to model the flexible catheter. The ensuing governing equations are solved via the classical Newton-Raphson-based nonlinear finite-element method. The computed results are validated against available benchmark tests for pre-magnetized magnetoelastic beams. The rigid confinements around the beam are modeled as straight or curved lines on which a no-penetration condition is applied. This no-penetration contact model is implemented via the classical Lagrange multiplier method. The beams exhibit snapping instability in a specific range of applied magnetic field magnitude and directions. At the onset of snapping, the effective Hessian matrix associated with the FE discretized system loses its positive definiteness. So, the classical Newton-Raphson method is not capable of realizing the unstable equilibrium configurations of the beam during snapping. Thus, pseudo-arclength-type algorithms are employed to capture this. Specifically, we have implemented the Crisfield, Ramm, and modified Crisfield-Ramm continuation algorithms to numerically realize the configuration of snapping beams under external magnetic fields. Viscous friction and the power law-type nonlinear friction between the beam tip and the obstacle wall reduce and eventually suppress the snapping with increasing coefficient of friction. Thus, via quantifying the snapping and non-snapping boundary, one can infer the nature of friction between the catheter tip and target tissue.

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