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Particle Separation Using Individually-Controlled Magnetic Soft Artificial Cilia

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Abstract : In this paper, a method based on soft artificial cilia is introduced to separate particles based on size and mass. In nature, cilia are used for fluid propulsion in the mammalian circulatory system, as well as for swimming and size-selective particle entrainment for feeding in microorganisms. Inspired by biological cilia, an array of artificial cilia was fabricated using Polydimethylsiloxane (PDMS) to simulate the actual motion. A row of four individually-controlled magnetic artificial cilia in a semi-circular channel are actuated by the magnetic fields from four permanent magnets. Each cilium is a slender rectangular cantilever approximately 13mm long made from a composite of PDMS and carbonyl iron particles. A time-varying magnetic force is achieved by periodically varying the out-of-plane distance from the permanent magnets to the cilia, resulting in large-amplitude deflections of the cilia that can be used to drive fluid motion. Previous results have shown that this system of individually-controlled magnetic cilia can generate effective mixing flows; the purpose of the present work is to apply the individual cilia control to a particle separation task. Based on the observed beating patterns of cilia arrays in nature, the experimental beating patterns were selected as a metachronal wave, in which a fixed phase lead or lag is imposed between adjacent cilia. Additionally, the beating frequency was varied. For each set of experimental parameters, the channel was filled with water and polyethylene microspheres introduced at the center of the cilia array. Two types of particles were used: large red microspheres with density 0.9971 g/cm^3 and 850-1000 μm avg. diameter, and small blue microspheres with density 1.06 g/cm^3 and diameter 30 μm. At low beating frequencies, all particles were propelled in the mean flow direction. However, the large particles were observed to reverse directions above about 4.8 Hz, whereas reversal of the small particle transport direction did not occur until 6 Hz. Between these two transition frequencies, the large and small particles can be separated as they move in opposite directions. The experimental results show that selecting an appropriate cilia beating pattern can lead to selective transport of neutrally-buoyant particles based on their size. Importantly, the separation threshold can be chosen dynamically by adjusting the actuation frequency. However, further study is required to determine the range of particle sizes that can be effectively separated for a given system geometry.

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