Nature-inspired microfluidic propulsion using magnetically-driven artificial cilia

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Summary In this work, we explore a new way to propel fluids through micro-channels of lab-on-a-chip devices by mimicking the fluid transport mechanisms of natural ciliates, such as Paramecia. Fluid propulsion of Paramecia takes place by means of hair-like motile appendages known as cilia that beat in an asymmetric manner. In addition, the individual cilia beat out-of-phase which results in a wave-like motion (metachronal waves). Here, we design magnetic artificial cilia that can be externally actuated to mimic these non-reciprocal deformations. The artificial cilia can be realized using thin films consisting of a polymer matrix filled with magnetic nano-particles, allowing actuation by means of an external magnetic field. We use a coupled magneto-mechanical solid-fluid model to explore the conditions at which a magnetic film will mimic the asymmetric motion of natural cilia. The response of the artificial cilia is studied in terms of the dimensionless parameters that govern their physical behavior and identify the parameter space in which the cilia can generate maximal flow.

INTRODUCTION

Lab-on-a-chip (LOC) is a technology that aims at performing chip-based analyses of biological samples (such as blood and urine), that are conventionally performed in a clinical lab. The analyses range from simple tests on biological samples to sophisticated DNA and cell analysis. As the surface to volume ratio is high in a LOC, physical phenomena associated with surfaces (e.g. surface tension and electrokinetics) gain importance. In addition, as the length scales involved are small, the viscous forces in the fluid dominate over the inertial forces leading to laminar flow profiles. An important consequence of this is that a non-reciprocal motion of an actuator is needed to effectively cause a net fluid transport. In this work, we explore a new way to manipulate fluids in microfluidic systems by mimicking the non-reciprocal micron-scale fluid propulsion mechanisms present in nature.

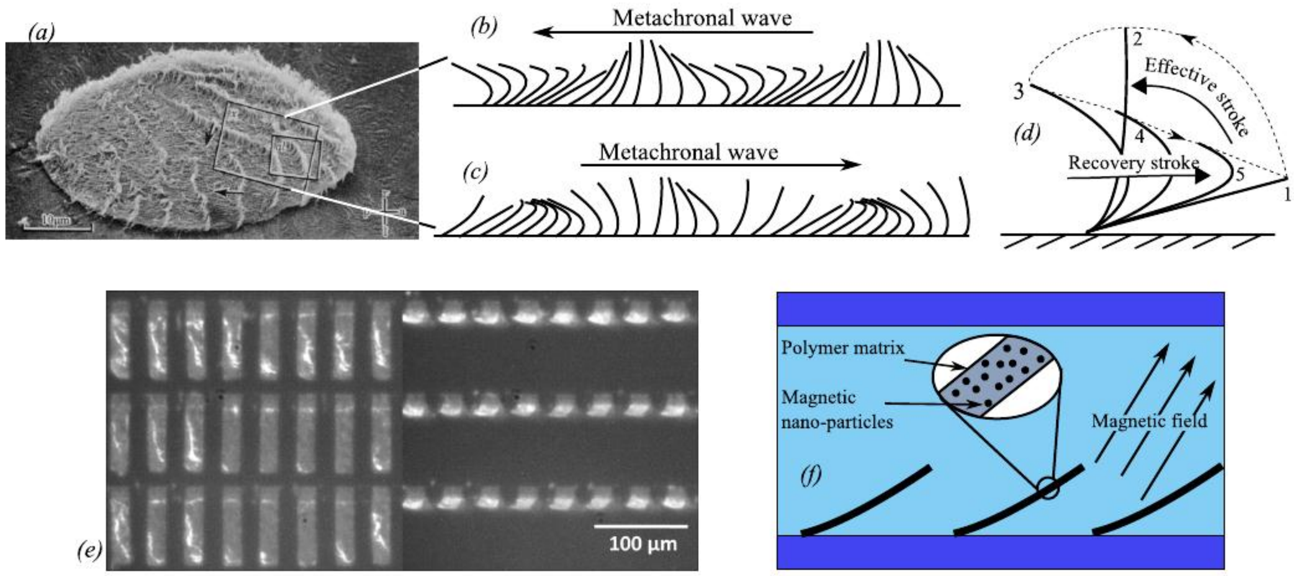


Figure 1: (a) A micro-organism (Opalina) uses hair-like structures called cilia for locomotion [1]. Cilia beat out-of-phase leading to the formation of (b) symplectic (the wave travels in the same direction as the effective stroke) and (c) antiplectic (the wave travels opposite to the effective stroke) metachronal waves. (d) The asymmetric motion of individual cilia consists of an effective and a recovery stroke. (e) Top view of magnetically-driven artificial cilia. Left: No magnetic field applied. Right: With magnetic field. (f) Schematic representation of the numerical model used. The cilia are made of soft polymer films with embedded magnetic nano-particles. A magnetic field is used to actuate the artificial cilia creating a fluid transport.

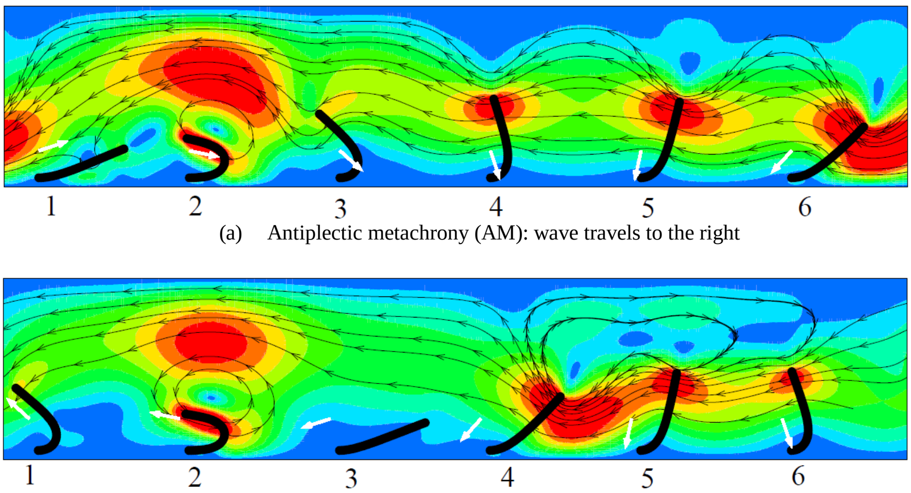
APPROACH

Non-reciprocal actuator motions have evolved in natural systems for mainly two reasons; locomotion and fluid propulsion (see Fig. 1(a)). These are often performed using hair-like motile appendages known as cilia that beat out-of-phase to result in a wave-like motion (see Fig. 1(b) and (c)). In addition, individual cilia beat in an asymmetric manner with a distinct effective and recovery stroke (see Fig. 1(d)). During the effective stroke the cilia are straight and push large amounts of fluid, whereas during the recovery stroke they stay closer to the cell surface and pull back a small amount of fluid. The net fluid propelled is in the direction of the effective stroke. The individual asymmetric motion of the cilia leads to a non-reciprocal motion, which, as such, creates flow. Moreover, natural cilia feature an additional collective symmetry-breaking mechanism consisting of the out-of-phase motion of neighboring cilia, resulting in metachronal waves. In this work we design artificial cilia that can be realized using thin films consisting of a polymer matrix filled with magnetic nano-particles, which can be actuated using an external magnetic field (see Fig. 1(e, f)). Depending on the nature of the particles, the film can be super-paramagnetic or ferromagnetic with a remanent magnetization.

MODEL AND RESULTS

The objective of this work is two-fold: *(i)* to identify for what geometries, material properties and applied magnetic fields a magnetic film will mimic the asymmetric motion of natural cilia, and *(ii)* to identify how the created flow can be enhanced by controlling different factors such as the cilia geometry, magnetic field, cilia spacing, channel height, fluid inertia and out-of-phase motion. We answer these questions using numerical models that capture the physical behaviour of magnetically-driven artificial cilia. The employed models predict the cilia deformation and the resulting fluid flow by simultaneously solving the Maxwell equations, solid dynamics equations and Navier-Stokes equations within a non-linear finite element framework.

One of the configurations in which the artificial cilia mimic the asymmetric motion of natural cilia is that of a tapered super-paramagnetic film fixed on the free end and subjected to a rotating magnetic field [2]. Using this configuration as a basis, we study various aspects of ciliary fluid propulsion as a function of the physical parameters that govern the flow created by the cilia in addition to geometric parameters such as the cilia spacing, channel height and phase difference between the cilia [3-4]. Also the effect of the wave direction (antiplectic versus symplectic metachrony) on fluid flow will be analyzed (see Fig. 2). Quantitative results are presented in terms of four dimensionless numbers, governing the relative contributions of the elastic, magnetic, fluid inertial and viscous forces. Using the insights gained from the analysis, we provide guidelines for the design of artificial cilia in a microfluidic channel that can be used in typical lab-on-a-chip applications.



(a) Antiplectic metachrony (AM): wave travels to the right

(b) Symplectic metachrony (SM): wave travels to the left

Figure 2: Snapshots for antiplectic and symplectic metachrony. The contours represent the absolute velocity (blue and red colours represent low and high velocities, respectively). The direction of the velocity is represented by streamlines. The applied magnetic field is shown by the white arrows. In both the cases the fifth cilium is in the peak of its effective stroke. In the case of symplectic metachrony, the effective flow created by the fifth cilium is obstructed by the close proximity of the fourth cilium, which has just started its effective stroke. As a result, we observe the formation of a vortex. In the case of antiplectic metachrony, however, the position of the fourth cilium is such that the flow created by the fifth cilium is not obstructed. This leads to larger fluid flow in the positive direction, so that the net flow created by antiplectic metachrony is larger than that created by its symplectic counterpart [4].

References

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