BEATING OF ARTIFICIAL MICROCILIA

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Summary We introduce of novel method combining soft-lithography and colloidal self-assembly to devise microfluidic devices patterned with slender magnetic rods. This novel setup is used to investigate the dynamics of extended cilia arrays driven by a precessing magnetic field. We show that the collective beating results in a symmetry breaking of the precession patterns. Using a minimal model, we show how the global geometry of the array imposes the shape of the trajectories via long range hydrodynamic interactions.

INTRODUCTION

Beating cilia are frequently used by cells to achieve propulsion, and to pump fluid at microscopic scales. Prominent examples include microorganisms, such as paramecia, algae, and ciliated epithelial tissues. Recently, these propulsion mechanisms have attracted much interest in the fluid mechanics and the biophysics communities. More precisely, the synchronization between beating cilia has motivated a surge in theoretical works [1], echoed by a few experimental studies on artificial [2] and biological setups [3]. So far, these experiments have mostly been dedicated to two-body problems. One of the main motivations for these works was to understand the role of the hydrodynamic coupling in the coordination of cilia beating in a viscous fluid. Most of the experiments and models have focused on the phase dynamics of these coupled active/actuated systems. Conversely, we report here on the beating *amplitude* of actuated microcilia carpets. In this paper we first introduced a method to devise artificial actuated micro cilia. We then take advantage of this unique model system to investigate, from a physical perspective, both the individual response and the collective dynamics of magnetic micro cilia driven by an external precessing field.

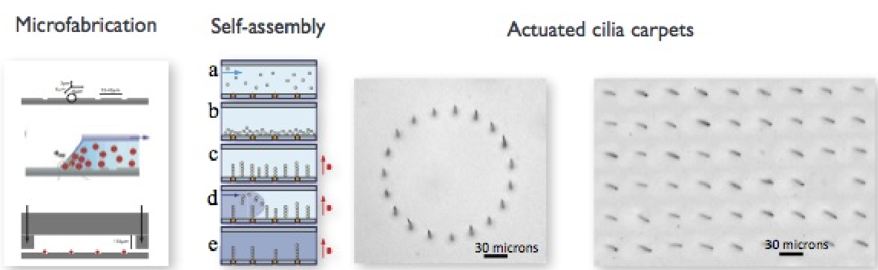

Figure 1. Sketch of the fabrication method, introduced in [4]. Left: capillary-assisted deposition of magnetic colloids in PDMS wells and sealing of a micro channel. Center: Self-assembly and ringing of magnetic cilia in a microfluidc chip. A fraction of the cilia aligns with magnetic anchoring sites at the bottom of the chamber. The others are rinsed away when a flow is applied, leaving an array organized in the geometry imposed by the magnetic template. Right: Resulting Microcilia carpets. The magnetic cilia are driven by a set of two Helmoltz coils.

PATTERNING OF MICROFLUIDIC CHANNELS WITH MAGNETIC CILIA

We combined soft lithography techniques and colloidal self-assembly to achieve the accurate patterning of PDMS thin films with magnetic microfilaments [4]. This hybrid method is illustrated in Fig. 1. In brief, we prepare a magnetic template by filling micro-fabricated wells in a PDMS sheet with large superparamagnetic colloids. This template is then used to close a conventional PDMS microchanel. We then inject a fresh magnetic-colloids solution in the resulting chip. We subsequently apply a DC magnetic field, and let the magnetized colloids to assemble into magnetic chains. Finally, we rince the setup with an aqueous solution. As a results all the self-assembled magnetic chains, but the one tethered to a magnetic anchor are flushed away. This simple a reproducible method make possible to isolate very small numbers of magnetic filaments, or conversely to devise extended cilia carpets of arbitrary shapes as illustrated in Fig. 1. In this example, the diameter of the cilia is $0.5\,\mu\mathrm{m}$, their length is $\sim 100\mu\mathrm{m}$.

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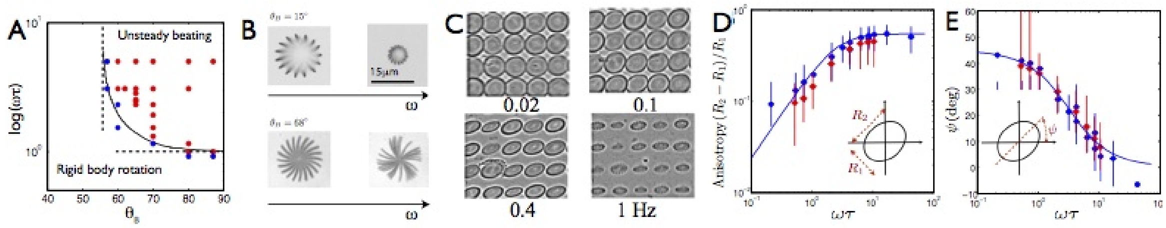

Figure 2. A: Phase diagram for the beating of an isolated cilium. B: Superimposition of snapshot taken at equal time intervals. The snapshots reveal an unsteady dynamics at high frequency and high field inclination. C- Trajectories followed by the tip of the cilia at various frequencies. Cilia length: 100μm, pitch: 30 μm, $B = 8mT$, $\theta_{\rm B} = 15°$

BEATING PATTERNS OF MAGNETIC MICRO CILIA: AN OVERVIEW

We now provide an overview of the dynamic response of such field responsive cilia when actuated by an homogeneous magnetic field. Before considering the case of hydrodynamical coupled cilia, we first report on the dynamic response of an isolated cilium.

Isolated cilium

We vary independently the amplitude B, the frequency ω, and the inclination θ_B of the driving field. By doing so, we establish a phase-diagram dividing the (θ_B, ω) plane into two extended domains, Fig. 1A: a linear response domain at low frequencies, and small inclinations, and a strongly non-linear domain for high values of these two control parameters. In the latter regime, the tip of the rod undergoes complex 3D beating patterns made of subsequent sequences of back and forth motions, Fig. 2. B. The dynamic transition between the two regimes defines two critical values for the field inclination and the actuation frequency. Interestingly the critical angle, $\theta_{\rm c} \sim 55°$, corresponds to the so-called magic angle and is independent of the material properties of both the fluid and the magnetic rod [4]. We will introduce a minimal model at the ITCAM 2012 conference to demonstrate how the geometrical non-linearities due to the magnetic actuation chiefly rule this nonlinear response.

Collective beating of micro cilia carpets

We now briefly review the collective behavior observed when a square lattice of cilia is actuated by an homogeneous precessing field. We restrained ourselves to the small inclination limit, where the single-cilia dynamics is linear. All the cilia rotates synchronously as an isolated filament would do. However, as show in Fig. 2C, the collective beating results in a symmetry breaking of the precession patterns [5]. The trajectories of the cilia are anisotropic and experience a significant structural evolution as the actuation frequency increases, as characterized in Fig. 2D. The anisotropy increases and plateaus as ω exceed the inverse of the typical relaxation time, $1/\tau$, of an isolated cilium. In addition, the orientation of the elliptical trajectories decays from an angle $45°$ with the channel main direction, to an angle of $0°$. These findings are rationalized by a minimal far field theory, where each cilia is modeled by a pointwise force source in the fluid. This model yields excellent agreement with our observations, Fig. 2D, [5]. It clearly explains how the global geometry of the array imposes the shape of the trajectories via long range hydrodynamic couplings. This will be demonstrated at the ITCAM 2012 conference.

To close this brief overview on our research on artificial microcilia, we shall add two last physical comments. Firstly, we note that, as the orientation of the filaments is slaved to the magnetic field, metachronal waves cannot propagate along artificial cilia carpets actuated in an homogeneous manner. However, the symmetry breaking of the beating trajectories should hold holds whatever the actuation mechanism, provided that the filaments: (i) have a finite response time to the driving torque and (ii) beat in a quasi synchronous fashion. Therefore, the very same structural changes in the beating patterns should be observed in carpets made of soft filaments actuated individually by a constant torque, which is the situation relevant for ciliated cells and microorganisms.

References

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