Electronic Supplementary Information (ESI) for *"Micro-fluidic actuation using magnetic artificial cilia"*, Lab on a Chip (2009)

1. Additional microscopy images of cilia

The microscopy images below reveal that the resolution of the fabrication process for artificial cilia is mainly limited by the large size of magnetic particle clusters. Fig. 8c below reveals that particle clusters are not only in the bulk of the cilia, because additional particle clusters have come to stick to the side of the cilia during the development process. Magnetic attractions are probably responsible for the presence of particles stuck to the side of the cilia. Dark field optical microscopy images in fluid give the impression that the cilia are only covered with magnetic particles, as can be seen in the movies and in Fig. 8b below. It should be realised that this impression is only an artefact of the dark filed microscopy in fluid. Because the refractive index of PDMS, water or isopropanol are close to each other, the PDMS cannot be seen clearly when immersed in fluid. Only the particles are revealed with high contrast, due to their fine structure and the dark field illumination. Fig. 8c shows the same cilium observed in a dry environment and reveals that large clusters are sticking out of the cilia while smaller clusters are completely within the bulk. Fig. 8d shows the cilium in dark field in a dry environment and provides a clear contrast between particles on the surface of the cilium (bright areas) and particles within the bulk (dark areas).

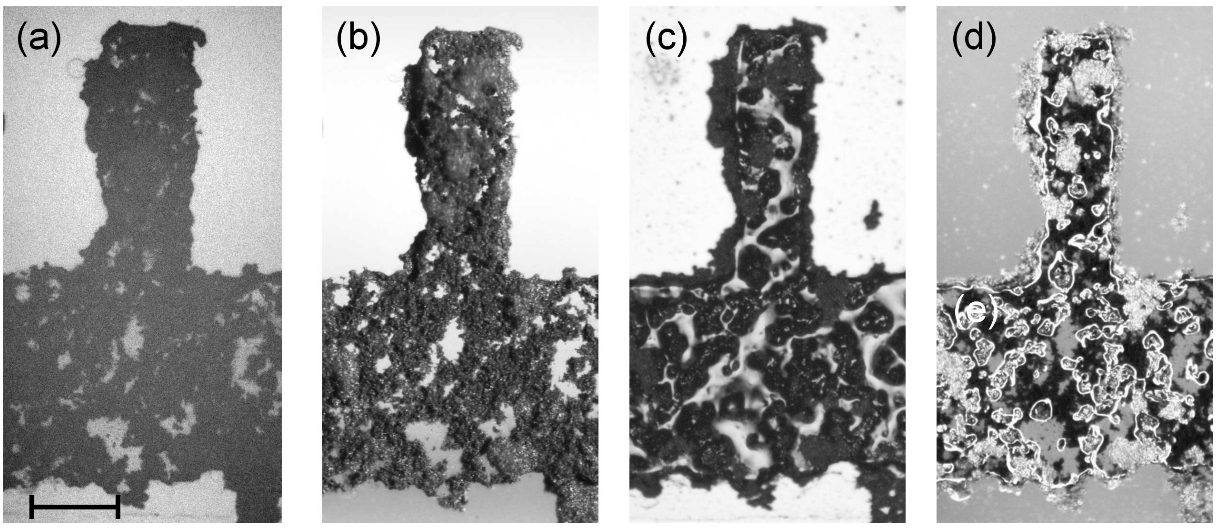

Fig. 8: *Optical microscopy images of an artificial cilium similar to the cilia shown in the movies and in Fig. 5 of the paper. The cilium has a thickness of 15 µm (perpendicular to the plane of the image) and contains 2 vol% of Fe-C particles. The scale bar indicates 100 µm. (a) The cilium is immersed in fluid and observed with bright field microscopy. (b) The cilium is immersed in fluid and observed with dark field microscopy. (c) The cilium is in a dry environment and observed with bright field microscopy. (d) The cilium is in a dry environment and observed with dark field microscopy.*

2. Movies of artificial cilia M1-M4

Movie 1, actuation of artificial cilia in fluid (*M1.wmv*)

Actuation of polymeric artificial cilia in a homogeneous rotating magnetic field with an induction of 50 mT. The manufactured cilia are 300 µm long, 100 µm wide and ~16 µm thick. They are made of PDMS and have a magnetic volume content of ~2%. Their elastic modulus is ~1 MPa. Experiments were performed in isopropanol. The frequency of rotation of the magnetic field was 0.1 Hz (quasi-static situation). Playback rate of the movie is double the real time.

The 3 same cilia are depicted in all 4 sub-movies with different directions of initial magnetisation. The right-most cilium is the cilium referred to as cilium C2 in the paper. The initial magnetisation was always performed with an induction of 100 mT before placing the cilia in the rotating field for actuation.

Top left :	Initial magnetisation in the long direction of the cilia. A symmetric movement is created.
Top right :	Initial magnetisation in the long direction of the cilia. Almost no movement is observed because the cilia are pointing in the opposite direction from the 3 other sub-movies, hence the magnetic field rotates in the opposite direction for this case. The absence of movement is explained in the paper.
Bottom left :	Initial magnetisation in the transverse direction. An asymmetric movement is created for the right-most cilium, by superposition of a torsion to the bending movement. The center cilium, which experiences less deflection, doesn't move asymmetrically since it comes back to its resting position between the torsion to one and the other side.
Bottom right :	Initial magnetisation in the other transverse direction. An asymmetric movement that is mirrored from the previous case is created for the right-most cilium.

Movie 2, actuation of artificial cilia in fluid at high frequencies (*M2.wmv*)

Actuation of a polymeric artificial cilium in a homogeneous rotating magnetic field with an induction of 50 mT. The manufactured cilium is 300 µm long, 100 µm wide and ~16 µm thick. It is made of PDMS and has a magnetic volume content of ~2%. Its elastic modulus is ~1 MPa. Experiments were performed in isopropanol.

The same cilium is depicted in all 6 sub-movies. The rotation frequency of the magnetic field was varied from 0.1 Hz to 50 Hz. For the highest frequencies the magnetic induction decreases due to eddy current losses in the electromagnet, but the amplitude of motion of the cilium is mainly limited by its viscous drag in the fluid. At 100 Hz the cilia ceases to move (not shown in movie).

Playback rate of the first sub-movie (0.1 Hz) is double the real time.

Playback rate of all other sub-movies (10 – 50 Hz) is 1/40 of the real time.

Movie 3, fluid manipulation of artificial cilia with asymmetric movements (*M3.wmv*)

Actuation of polymeric artificial cilia in a homogeneous rotating magnetic field with an induction of 30 mT. Experiments are performed in a microchannel (2 cm long, 2 mm wide and 400 µm high) filled with water containing 3.15 µm polystyrene tracer particles. The field of view of the movie is 1.8 mm x 0.7 mm.

In the first part of the movie, the movement of 4 cilia is shown in bright field microscopy with an actuation frequency of 0.2 Hz. It can be seen that mainly the two outer cilia have an asymmetric movement while the movement of the two inner cilia is almost symmetric. Later in the first part of the movie, dark field microscopy reveals with more contrast the movement of the tracer particles.

The second part of the movie shows the same 4 cilia and is performed with an actuation frequency of 5 Hz. One shot is taken per rotation cycle of the magnetic field. It is clearly visible that the two outer cilia are inducing large local vortices. The flow induced locally by the right-most cilia is presented in Fig. 7a of the paper.

Playback rate of the entire movie is double the real time, independently of the actuation frequency..

Note that a defective cilium is visible on the left. This cilium was very compliant and got stuck in a bent-over situation after the first actuation cycle, by adhering to the PDMS. Therefore, care should be taken that the cilia do not bend up to 180°, which can be controlled once the fabrication procedures have been optimised to create uniform artificial cilia that all have the same response.

Movie 4, fluid manipulation of artificial cilia with (a-priori) symmetric movements *(M4.wmv*)

Actuation of polymeric artificial cilia in a homogeneous rotating magnetic field with an induction of 30 mT. Experiments are performed in a microchannel (2 cm long, 2 mm wide and 400 µm high) filled with water containing 3.15 µm polystyrene tracer particles. The field of view of the movie is 0.8 mm x 0.95 mm.

In the first part of the movie, the movement of 3 cilia is shown in bright field microscopy with an actuation frequency of 0.2 Hz. The cilia have an almost symmetric movement (*i.e.* witout torsion). Later in the first part of the movie, dark field microscopy reveals with more contrast the movement of the tracer particles.

The second part of the movie shows the same 3 cilia and is performed with an actuation frequency of 5 Hz. One shot is taken per rotation cycle of the magnetic field. The cilia do not induce vortices as in movie M3 and the fluid movement is locally translational. In the paper we conclude that the fluid movement is created by a slight asymmetry in the otherwise symmetric movement of the cilia. The flow induced locally by the 3 cilia is presented in Fig. 7b of the paper.

Playback rate of the entire movie is double the real time, independently of the actuation frequency.

Remark on Movie 3 and 4

The cilium with (a-priori) symmetric movement shown in the upper left part of movie M4 is the same cilium as the right-most cilium with torsional asymmetric movement shown in movie M3. Because of the different initial remanent magnetisations in movies M3 and M4, the net fluid flow induced by the same cilium is very different (rotational or translational).