Details of selected paper

Title: Magnetic and Viscous Drag Torque of Microfabricated Elements and Magnetotactic Bacteria

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Text

We measured the maximum angular velocity of self-propelling magnetotactic bacteria subjected to a rotating magnetic field. To predict this value, we assumed a simple model in which the magnetic torque is balanced by the rotational viscous drag torque. This model was validated by measuring the maximum angular velocity of microfabricated silicon-nitride elements with a Co80Ni20 magnetic strip floating on the water surface. We show that our model predicts maximum angular velocities reasonably well, and can be used to predict trajectories of magnetotactic bacteria under applied field conditions.

Magnetotactic bacteria possess chains of magnetosomes, consisting of iron-oxide nanocrystals on which the earth magnetic field can exerts a torque, allowing the magnetotactic bacteria to locate the bottom of water columns (Figure 2, top) Since magnetotactic bacteria are self-propelling, they can be used to transport payloads (Martel, 2010) and can be controlled up to 20 micrometers accurately using electromagnets (Khalil, 2013). Of key importance for control is the minimum radius of curvature of the bacterium trajectory, which is the ratio of forward speed and maximum angular velocity.

Since a colony of magnetotactic bacteria shows a large spread in morphology and magnetic properties, we designed a model system to investigate magnetic and rotational drag torque. By means of microfabrication, we realised free standing silicon-nitride structures of 100-500 um length and 50-100 um width, with a rectangular Co80Ni20 thin film bar (Figure 1). The structures were broken from their support by tweezers, and floated on a water surface under a microscope objective. Subsequently, we observed their rotation under application of a rotating magnetic field generated by a set of electromagnets.

The magnetic torque of the microfabricated elements was modeled using a line charge approach, and measured on a large array of bars by means of torque magnetometry. The field dependence of the magnetic torque agrees withing measurement error with the torque model. The viscous drag of rotating silicon-nitride elements was modeled using a Stokes flow approach. Since the viscous drag torque is proportional to the angular velocity, the maximum angular velocity can be obtained by equating the magnetic and drag torque. Even though the model is simple, the maximum angular velocity agrees well with observations of rotation (Figure 1, bottom).

The magnetic torque that an external field can exert on the magnetosome inside the magnetotactic bacterium was modeled by a finite element method based on magnetic charges. We show that the FEM results can be approximated by a compact analytical model based on a chain-of-dipoles approximation with an accuracy better than 1%. The viscous drag torque was calculated assuming that the bacteria are ellipsoidal in shape. Using SEM and TEM imaging to obtain the dimensions of the bacteria and magnetosomes respectively, the maximum angular velocity was calculated to range from 4 to 30 rad/s. The spread is caused by the distribution of dimensions within the colony of bacteria. This range agrees well with our observation of a randomly selected bacteria, which showed a maximum rotational velocity of magnetotactic bacteria in the order of 10 rad/s (figure 2) under application of a 7.9 mT field. Our models predict that the maximum velocity can be increased by a factor of two.

The model we propose is of primary importance to the field of self-propelled medical microrobots that use external magnetic fields to steer the direction of movement, which include next to magnetotactic bacteria also microrobots that gain energy from a time varying external magnetic field (Zeeshan, 2013) or the surrounding fluid (Sanchez, 2011).

Figure 1: Top: Magnetic torque of an array of microfabricated Co80Ni20 thin film rectangles as a function of applied field. Bottom: The maximum rotation frequency of rectangular silicon nitride elements with Co80Ni20 bars (see inset) decreases with object length. A simple theory based on the balance between magnetic and rotational viscous drag is predicting the maximum rotation frequency reasonably well.

Figure 2: Magnetotactic bacteria (SEM image, left) use a chain of magnetic crystals (TEM image, right) to orient themselves along the earth magnetic field. Bottom: By applying a rotating magnetic field with increasing angular velocity, the maximum rotation frequency for a magnetotactic bacterium can be determined. In this case the bacterium, indicated by the red arrow, looses track at the frame at 8.2 s, corresponding to a frequency of 10 rad/s. Using the simple theory developed and tested for microfabricated elements, the maximum magnetic moment that can be exerted by an external field on the bacterium can be estimated to be in the order of 4 Nm.

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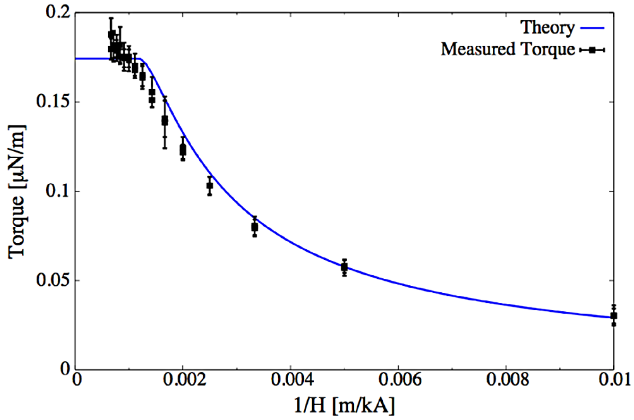

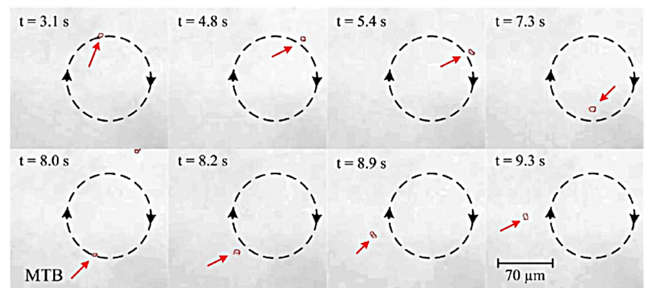

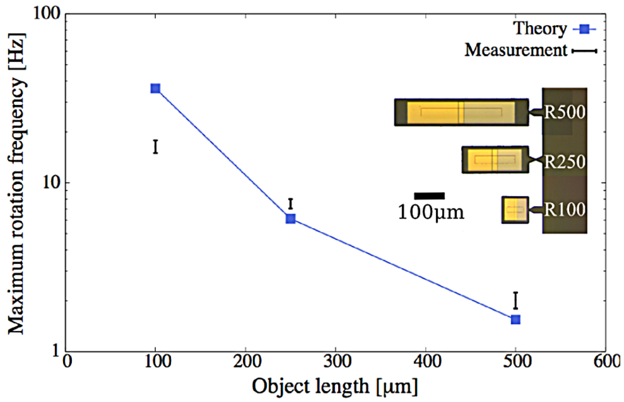

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