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Magnetic field driven nanowire rotation in suspension

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Magnetic field driven nanowire rotation in liquids has been investigated. This approach provides a noncontact, sensitive, cost effective, and easy to scale up scenario to manipulate the motion of magnetized one-dimensional nanostructures for "nanomachine" and anisotropic nanomaterial development. Due to the small dimensions, viscous behavior dominates the nanowire motion. Qualitative analyses considering the competing magnetic field induced torque and resisting fluid drag torque have been conducted for nanowire rotation under different circumstances. The analyses and experimental observations can provide key information for the understanding of hydrodynamics at the nanoscale. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2789184]

Manipulating nanoscale entities is a challenging yet necessary task in nanoscience and nanotechnology development. For example, to align carbon nanotubes or nanofibers, approaches utilizing the Langmuir-Blodgett method,[1] microfluidic channels,[2] electrospinning,[3] strong magnetic and electric fields,[4–7] and high shear forces[8] have been explored. Yet, it has been shown that precise and reproducible manipulation of nanoentities in large volumes still remains as one of the major technical hurdles. Using optical tweezers, it is now possible to trap and drive individual particle motion,[9–12] but the light wavelength and scattering limit the particle sizes that can be operated. Moreover, high rotational speed is difficult to achieve due to the weak forces and heat generated by light. Recently, controlled rotation of nanowires based on electrorotation and dielectrophoresis has been reported.[13–15] These approaches normally require lithographic patterning or micromachining to fabricate electrodes for strong field generation in limited space. In addition, the electrochemical stability of fluids has to be considered. Here, we report a low-cost, easy to implement, and noncontact approach that can effectively manipulate the motion of "magnetized" one-dimensional materials using magnetic field. With the capability of incorporating magnetic coatings or segments, a wide range of materials can be manipulated by the magnetic field and thus lead to the development of various bio/chemical "nanomachines"[16] and functionalized nanostructures.

Nanomaterial manipulation is normally performed in liquids to reduce surface van der Waals influences, and their motion is mainly controlled by the external driving force and the liquid drag force [Fig. 1(a)]. Usually, the external forces can be well quantified, so the ability to predict nanowire behavior relies on the determination of the drag force. Classical hydromechanical models describing translational motion of ellipsoid/cylinder or rotation around a long axis are well established.[17–19] However, for a cylinder rotating around its midpoint, a complex velocity field is created due to the velocity variation along the wire. No analytical solution for the drag coefficient is available.[20–22] Therefore, an estimation based on translational motion results is developed.

In the Stokes flow region, the fluid drag force F_d is directly proportional to the velocity V ($F_d=DV$). For a high aspect ratio prolate spheroid moving perpendicular to its long axis, the drag coefficient D can be expressed as[17–19]

$$D=\frac{4\pi\eta L}{\ln[L/r]+0.5}, \tag{1}$$

where η is the dynamic viscosity of fluid, and L and r are the length and radius of the spheroid, respectively. The rotating nanowire is divided into N segments with individual lengths of $\Delta l=L/N$, and the prolate spheroid approximation is applied [Fig. 1(b)]. The total drag torque is estimated by the summation over all segments as

$$\tau_d=2\sum_{n=1}^{N/2}\frac{\omega_w l_n 4\pi\eta\Delta l}{\ln(\Delta l/r)+0.5}l_n=\frac{1}{3}\omega_w\pi\eta L^3\frac{N^3-N}{N^3[\ln(L/Nr)+0.5]}$$

$$=\frac{1}{3}\omega_w\pi\eta L^3 C, \tag{2}$$

where ω_w is the angular rotation speed and $l_n=(n-1/2)\Delta l$.

Equation (2) shows a linear correlation between the drag torque and L^3 for every specific nanowire. This satisfies the dimensional homogeneity requirement and is consistent with

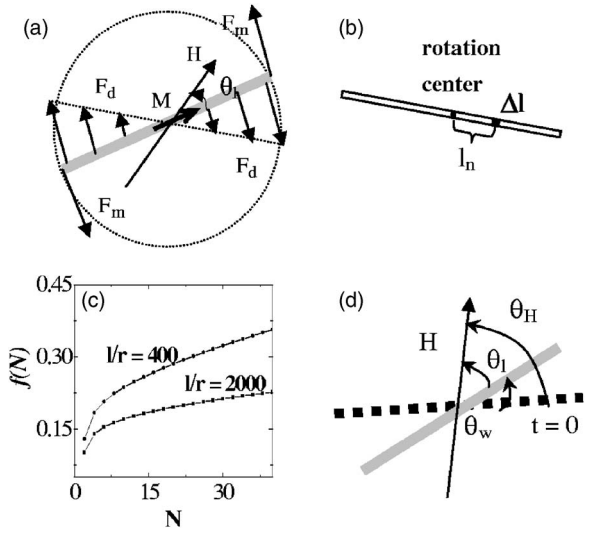

FIG. 1. Schematics of (a) the magnetic driving force (F_m) and the drag force (F_d) on a rotating nanowire in liquid, (b) the wire being divided into N equal pieces for the estimation of drag coefficient, (c) the geometric factor C as a function of the number of segments N, and (d) geometric relations for nanowire rotation.

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the experimental observations reported by Chien *et al.*[13] The calculations in Ref. 14 correspond to $N=2$. Figure 1(c) describes the value of C as a function of N with two nanowire aspect ratios of 400 and 2000. In this analysis, the choice of N cannot be specified except that the choice of N has to satisfy $L \gg r$ so that Eq. (1) is valid. In our calculations, $C=0.15$ is used. For a nanowire with an aspect ratio of 400, this C value corresponds to $N=4$.

The schematic of the geometry during nanowire rotation is shown in Fig. 1(d). The dotted line represents the original nanowire position at time $t=0$. $\theta_w(t)$ and $\theta_H(t)$ define the nanowire and field angles. θ_l is the lag angle between the wire and the field. Corresponding angular velocities (ω) and angular accelerations (α) satisfy

$$\theta_H(t) = \theta_w(t) + \theta_l(t),$$

$$\omega_H(t) = \omega_w(t) + \omega_l(t),$$

$$\alpha_H(t) = \alpha_w(t) + \alpha_l(t). \tag{3}$$

For a nanowire being placed in a uniform magnetic field H, the driving torque is

$$\tau_m = \mathbf{m} \times \mathbf{H} = M_s \pi (r^2) HL \sin \theta_l, \tag{4}$$

where m is the magnetic moment and M_s is the spontaneous magnetization. For nickel nanowires, $M_s = 485 \times 10^3$ A/m is used.

The nanowire rotation is determined by

$$\tau_m - \tau_d = I \alpha_w(t) \quad \text{with } I = \pi r^2 \rho L^3/12, \tag{5}$$

where I and ρ are nanowire's moment of inertia and mass density, respectively. Combining Eqs. (2), (4), and (5), the governing equation has the form

$$\frac{d^2\theta_w(t)}{dt^2} + \frac{4\eta C}{r^2\rho}\frac{d\theta_w(t)}{dt} - \frac{12M_sH}{\rho L^2}\sin\theta_l(t) = 0. \tag{6}$$

Consider the nanowire motion under the influence of a rotating external field with an angular velocity ω_H. Equation (6) can be rewritten as

$$\frac{d^2\theta_l(t)}{dt^2} + \frac{4\eta C}{r^2\rho}\frac{d\theta_l(t)}{dt} + \left[\frac{12M_sH}{\rho L^2}\sin\theta_l(t) - \frac{4\eta C}{r^2\rho}\omega_H\right] = 0. \tag{7}$$

Assume the nanowire and field are aligned initially, and the field begins to rotate at $t=0$. When the field begins to rotate away, the driving torque increases and thus speeds up the nanowire. Larger θ_l results in larger magnetic torque and acceleration. The nanowire then achieves a stabilized state with a constant θ_l. With $\omega_w = \omega_H$ and $\omega_l = 0$, the stabilized θ_l can be determined by

$$\theta_l = \sin^{-1}\left[\frac{\eta L^2 C \omega_H}{3M_s r^2 H}\right]. \tag{8}$$

$\theta_l = 90°$ corresponds to the maximum nanowire rotation speed where $\tau_m = \tau_d$. This maximum speed can be determined as

$$\omega_{w,\max} = \frac{3M_s r^2 H}{\eta L^2 C}. \tag{9}$$

For the Ni nanowire with length of 40 μm and radius of 100 nm rotating in water ($\eta = 0.89$ mPa s) with an applied field of 4.6×10^{-4} T, $\omega_{w,\max}$ is calculated to be 31.5 rad/s.

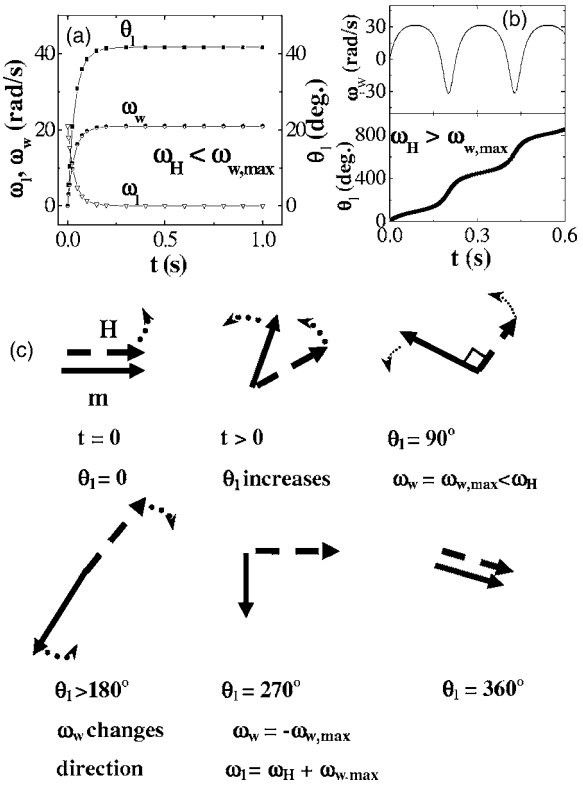

FIG. 2. Calculated variations of ω_w and θ_l at (a) low driving speeds and (b) high driving speeds. (c) Variation of θ_l between nanowire and field when $\omega_H > \omega_{w,\max}$. Here, H is the field and m is the nanowire magnetic moment.

As shown in Fig. 2(a), as long as the driving field speed does not exceed $\omega_{w,\max}$, synchronous nanowire rotation can be achieved. However, if driving speed goes above $\omega_{w,\max}$, nanowire rotation will lose its synchronization with field. Figure 2(b) summarizes the variations of ω_w and θ_l when $\omega_H > \omega_{w,\max}$. As shown in Fig. 2(c), as the field rotates away from the nanowire, the driving torque, ω_w, and θ_l increase. The nanowire achieves the maximum speed $\omega_{w,\max}$ at $\theta_l = 90°$. For $90° < \theta_l \leq 180°$, ω_w decreases from $\omega_{w,\max}$ to zero due to the decreasing driving torque. When θ_l is beyond 180°, the nanowire starts to rotate in the opposite direction to the driving field. At $\theta_l = 270°$, $\omega_w = -\omega_{w,\max}$. When $\theta_l > 270°$, the magnitude of ω_w decreases. At $\theta_l = 360°$, $\omega_w = 0$. Then, this process repeats itself.

In experiments, Ni nanowires were fabricated by template-assisted electrodeposition in porous alumina templates. Experimental details can be found elsewhere.[23,24] A representative scanning electron microscopy (SEM) image of the Ni nanowires is shown in Fig. 3(a). Nanowire rotation in suspension was recorded by a charge coupled device (CCD) camera (PL-A741, Pixelink) connected to an optical microscope. The frame rate was 50 frame/s at a resolution of 640×480. A uniform magnetic field was generated by a set of Helmholtz coils (custom designed based on a HC-3 from Magnetic Instrumentation, Inc.), which has a field uniformity of 0.5% in a cylindrical volume of 1 in. long and 1 in. in diameter.

Figure 3(b) shows the snapshots of two nanowires rotating with a magnetic field in ethylene glycol ($\eta = 16$ mPa s). The relation between the angular velocities of nanowire and driving field is summarized in Fig. 3(c). At low driving speeds, nanowire rotates synchronously with the field. At

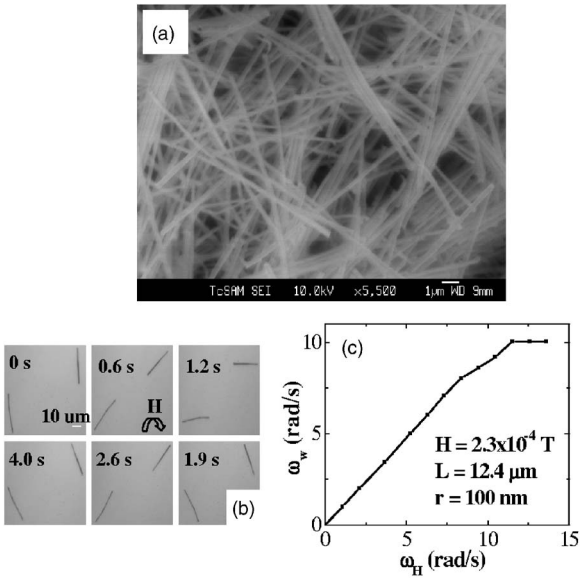

FIG. 3. (a) SEM micrograph of the Ni nanowires grown in alumina membrane, (b) optical micrographs of two Ni nanowire rotating synchronously with magnetic field in ethylene glycol, and (c) relationship between angular velocities of wire and field.

high driving speeds, reversal nanowire rotation has not been observed. This might be due to our CCD speed and the short time period of the reversal motion. When the average angular velocity of the nanowire was monitored, it deviated from the linear correlation with driving speed and decreased when $\omega_H > \omega_{w,\max}$. This can only be explained by the reversal rotation of the nanowire in responding to higher driving speeds. An extreme case will be when the driving field frequency is very high and the nanowire will keeps oscillating around its position. Based on Eq. (9), it can be seen that increasing the magnitude of the magnetic field will be an effective way to improve the achievable nanowire speed.

In summary, we demonstrated the control of nanowire rotation in fluids using magnetic field. The development of next generation nanomachines—such as drug delivery vehicles, on-board nanoagitation devices, nanolight polarizer, as well as self-assembled structures and nanocomposites—requires efficient manipulation of nanoparticle motion. Magnetic field manipulation provides a noncontact, sensitive, easy to scale up, and cost effective solution to the problem. The analysis developed here is applicable to general problems of one-dimensional structure motion driven by external forces. However, only a rough approximation of the fluid drag torque for the rotating nanowire (around midpoint) has been established here. We expect that the experimental approach and observations here can stimulate further exploration of more accurate nanoscale fluid dynamics models. If successful, this external field driven nanowire rotation method can be used to probe fluid properties.

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