Deformation of flexible ferromagnetic filaments under a rotating magnetic field

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ABSTRACT

Research on magnetic particles dispersed in a fluid medium, actuated by a rotating magnetic field, is becoming increasingly active for both lab-on-chip and bio-sensing applications. In this study, we experimentally investigate the behaviour of ferromagnetic filaments in a rotating field. Filaments are synthesized by linking micron-sized ferromagnetic particles with DNA strands. The experiments were conducted under different magnetic field strengths, frequencies and filament sizes, and deformation of the filaments was registered via microscope and camera. The results obtained showed that the body deformation is larger for longer filaments and higher frequencies and lower for larger magnetic field. The angle between the filament tangent at the centre and the magnetic field direction increases linearly with frequency at low-frequency regime. A further increase in the frequency will result in filament movement out of plane when the angle approaches 90 degrees. The experimental results were used to estimate magnetic moment and the bending elasticity of the filament.

1. Introduction

Flexible magnetic filaments are interesting for different applications, microfluidic mixing [1] and transport [2], sensors [3], creating self-propelling magnetic microdevices and others [4]. For these applications interesting are ferromagnetic filaments, which may be created by linking ferromagnetic microparticles [5]. Several interesting phenomena are known for ferromagnetic filaments - in the AC magnetic field with a frequency high enough they orient perpendicularly to the field [5]. When magnetic field direction is changed, filaments form snake like 'S' shape [6]. If the direction is inverted, ferromagnetic filament makes a loop [7], which further relaxes by 3D motion. Due to the loop formation it is possible to create self-propelling magnetic microdevices [8].

Considerable effort has been put to numerical modelling of flexible magnetic filaments. For example, small filament behavior under constant field have been investigated in dilute regime [9] and under external flow [10]. Dynamics of a filament in rotating field has been studied in [11].

In the present work we investigate physical properties of ferromagnetic filaments under rotating magnetic field, focusing on the deformation dependence on the frequency and strength of the field.

2. Experimental

2.1. Synthesis

The filament synthesis methodology was adapted from [12]. In this way filaments with a length $L$ between 8 $\mu$m to 80 $\mu$m are formed. For example, see Fig.1(a). The filaments were prepared by mixing $4.26 \mu$m large ferromagnetic particles (Spherotech) with DNA strands (ASLA biotech) in TE buffer (10%) solution. Ferromagnetic particles are made from polymer beads, that are covered with Chrome dioxide. Their surface is functionalized with streptavidin. DNA strands are 1000bp long and have biotin at their ends. In the solution we use DNA to particle's mass ratio of 0.18.

Each sample was made in a 1.5 ml tube by mixing 0.5 ml TE buffer solution ($\eta = 0.01$ P) with 10 $\mu$L of DNA solution and 2 $\mu$L particle suspension. The sample is then quickly placed in the middle of two $5 \times 5 \times 1$ cm Neodymium magnets, fixed 7 cm apart, providing a homogeneous field of $\approx 500$ Oe. It is left in the field for two minutes, allowing particles to form chains. While chains are formed, biotin ends of DNA find their way to streptavidin surface of beads and link the particle chains permanently.

2.2. Video microscopy

Filaments were observed with an optical microscope (Leica DM1300B) using a 40× objective in bright field mode. The magnetic field is generated using a coil system consists of six coils placed to provide fields in three directions. An AC power supply (Kepco BOP 20-10M) connects with the coil pairs in each direction, which is capable of producing fields of up to 120 Oe, with a maximum frequency of 50 Hz. The current output is controlled using National Instruments data acquisition card and LabVIEW code. It generates analogue sine and cosine signals for a rotating magnetic field. The fluidic cells are prepared using two glass slides separated by 130 $\mu$m double-sided adhesive tape. Each cell is formed by a $1 \times 1$ cm cut in the tape, in which 10 $\mu$L of the prepared solution are added. The images are taken using Basler ac1920-155um camera. Depending on the measurement, it is used either in a fixed frame rate, for which a maximum of 200 fps can be achieved, or by a trigger mode, which allows to synchronize it with the magnetic field direction.

2.3. Image processing

The images used for characterising the filament deformation were obtained by trigger mode in a way that the mag-
Figure 1: Behavior of two flexible magnetic filaments under rotating magnetic field $H = 8.6$ Oe. Filament with $L = 67.4 \mu m$ at (a) 0.2 Hz, (b) 0.3 Hz, (c) 0.4 Hz and (d) 0.6 Hz. Filament with $L = 50.5 \mu m$ at (e) 1.0 Hz, (f) 1.5 Hz, (g) 2.0 Hz and (h) 3.0 Hz. In (h), the filament moves out of imaging plane.

Figure 2: (a) An illustration of filament image processing. Polynomial fit (black curve) of centres of particles (blue asterisks and red circles) describes the deformed filament. The angle ($\theta$) between the tangent at the filament center (blue dashed line) and the magnetic field direction (indicated with the black arrow) is used for characterizing deformation. (b) An example of deformation relaxation measurement. The position of filament tip particle ($y$-displacement) is tracked over time. (c) Experimental magnetic filament deformations for different frequencies $f$ (0.2, 0.4, 0.5 and 0.6 Hz) at $H = 8.6$ Oe.

This allows to find the tangent at the centre (blue dashed line) and calculate the angle $\theta$.

Experiments for analysing the deformation relaxation time were obtained by setting the frame rate to 150 fps. Initial deformation of the filament is made by a rotating magnetic field having strength values between 8.6 Oe and 17.2 Oe. Then magnetic field is turned off and the relaxation is observed, while tracking the displacement of the filament tip particle. An example of processed image for tracking the displacement of tip particle $y(t)$ is shown in Fig.2(b).

3. Results and Discussion

The experiments were conducted in the following manner. The fluidic cell is placed for observation under the microscope. Due to gravity effects, the filaments sediment to the bottom of fluidic cell. A static magnetic field of 17.2 Oe is applied in the north direction. A rotating field is then applied having magnetic strength $H$ values between 6 Oe and 25 Oe, with frequencies up to 8 Hz. The image acquisition is set to trigger mode. Characteristic images of deformed filaments can be seen in Fig.1.

Increase of a frequency induces a larger deformation of the filament. This can be clearly seen in Fig.2(c), where filament polynomial fits for various frequencies (0.2 Hz (red curve), 0.4 Hz (blue curve), 0.5 Hz (green curve) and 0.6 Hz (black curve)) at fixed magnetic field strength $H = 8.6$ Oe are compared.

Measurements were done for filaments with different length. The results show that longer filaments have higher angle $\theta$ at a fixed frequency and field strength. Hence, longer filaments tend to deform more, while having more flexibility to
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Figure 3: Relationship between the angle $\theta$ and frequency under rotating magnetic field, $H = 6.9$ Oe, for filaments with different lengths: $L = 46.2$ $\mu$m (blue line), $L = 37.9$ $\mu$m (red line) and $L = 16.8$ $\mu$m (green line).

Figure 4: Relationship between the angle $\theta$ and frequency under rotating magnetic field with different strengths, $H = 8.6$ Oe (red line), $H = 17.2$ Oe (blue line) and $H = 25.8$ Oe (green line), filament length $L = 46.3$ $\mu$m.

deform by viscous torques under a rotating field. Angle as a function of the frequency for different filament lengths is shown in Fig.3.

The results for the effect of varying magnetic field strength $H$ and frequency $f$ was obtained using a single filament for each analysis. The rotating magnetic field introduces a magnetic torque, which is a function of the field strength opposed by viscous torque, dependent on the length $L$ and the angular velocity $2\pi f$. The increase of the frequency at a constant $H$ increases the characteristic angle $\theta$. Results are shown in Fig.4. At low frequencies this relationship is found to be linear. A further increase in the frequency tends to lower the gradient as a result of the increased viscous forces. The filament tends to deform having ‘S’ like shape as visible in Fig.1(g), where the filament centre tends to orient perpendicular to the magnetic field direction, while the tips try to follow the field, but orient in an angle that reaches up to $60^\circ$.

The effect of increasing the field strength $H$ at constant frequency decreases the deformation and angle $\theta$, due to the increased torque to overcome the friction forces.

In these experiments filaments were found to move synchronously with magnetic field (data not shown). This is different than observed in numerical modelling by Goyeau et al. [11]. There, if frequency is increased, the filaments reach an asynchronous regime, where the filaments experience back and forth motion due lag in following the magnetic field. In comparison, in experiments a further increase in $\theta$ results in filament movement out of the image plane, in the third dimension. This transition was noted to occur when the filament centre orients perpendicularly with the field direction, having $\theta$ of $90^\circ$. An example of this behavior visible in figure Fig.1(h). As a result, we can assume that small fluctuations deform the filament to a three dimensional shape, which is dynamically preferable, before it reaches an asynchronous regime.

Similar deformed ‘S’ like filament shapes with back and forth motion can be observed for paramagnetic filaments in specific rotating magnetic field conditions [13]. However, the difference in magnetic properties does not allow to compare the behavior quantitatively.

For our experiments we can describe the angle $\theta$ dependence by a theoretical model for filament dynamics under rotating field presented in Erglis et al. [7], where numerical simulations give the following relation

$$\theta = 0.086 \frac{\omega \tau}{C_m},$$  

(1)

where $\tau$ is the elastic deformation time $\tau = \frac{\zeta L^4}{A_b}$, $\omega$ is the angular velocity $\omega = 2\pi f$ and $C_m$ is the magnetodynamic number, $C_m = \frac{MHL^2}{A_b}$ for which $L$ is the filament length, $H$ is the magnetic field strength, $A_b$ is the bending modulus and $\zeta$ is the hydrodynamic drag coefficient which is estimated by $4\pi n$.

We use relation (1) to analyze the linear regimes in Fig.4. Slopes $\frac{\Delta \theta}{\Delta f}$ as a function of $\frac{1}{H}$ for a filament $L = 46.3$ $\mu$m are shown in Fig.5. The experimental data is fitted with a linear relation $\frac{\Delta \theta}{\Delta f} = a \frac{1}{H}$, for which we find $a = 6.8$ Oe-s. From this we find information about filament magnetization. For magnetization per unit length we get $M = 2.14 \cdot 10^{-7}$emu and for the magnetic moment of particle $m = 9.01 \cdot 10^{-11}$emu (M-d). The last value is not far from estimates in [7].

In order to measure bending modulus, the protocol for filament relaxation was carried out, as explained in §2.3. The motion of the filament tip shows an exponential time dependence, as can be seen in Fig.6. The decrements of relaxation are different for different filament length and are found to be equal to 0.25 $s^{-1}$ for $L = 80.0$ $\mu$m, 0.42 $s^{-1}$ for $L = 67.4$ $\mu$m and 0.94 $s^{-1}$ for $L = 63.2$ $\mu$m. It is worth to note that in our experiments the filament does not return to its original shape, as visible in Fig.2(b). Small remaining deformation may be the result of damaged bonds between the particles or due to wall surface drag.
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Figure 5: Relationship between $dA/df$ and $1/H$, obtained for a filament with length $L = 46.3 \, \mu m$.

Figure 6: Filament relaxation behaviour for different filament length and initial rotating field conditions: $L = 80.0 \, \mu m$, $f = 1.0 \, Hz$ and $H = 8.6 \, Oe$ (red curve). $L = 63.2 \, \mu m$, $f = 1.0 \, Hz$ and $H = 13.7 \, Oe$ (blue curve). $L = 67.4 \, \mu m$, $f = 1.5 \, Hz$ and $H = 8.6 \, Oe$ (green curve).

Figure 7: Relationship between relaxation decrements and $L^{-4}$ for different filament lengths. Black circles are experimental points with errorbars. Red dashed line is linear fit and red dotted lines are confidence intervals for $3\sigma$.

The filament relaxes due to the action of bending elasticity and is slowed down by viscous forces. The solution of the elasticity problem for the rod at free and unclamped boundary conditions [14] gives the spectrum of relaxation rates from which the smallest decrement is given by relation $3.93^4 L^{-4} A_b/\zeta$. Taking experimental values of decrements and fitting as a function of $L^{-4}$ allows to estimate the average bending modulus of the rod. This is done in Fig.7. The fitted line and its error gives $(A_b \pm \Delta A_b) = (6.5 \pm 3.4) \cdot 10^{-13}$ erg-cm. This is close to the estimate of bending modulus obtained in [5].

4. Conclusions

Properties of ferromagnetic filaments synthesized by linking functionalized ferromagnetic microparticles by biotinized DNA fragments are measured by the study of their deformation in a rotating magnetic field. It is found that filaments at low frequencies have ’S’ like shapes and the tangent angle at the center of filament is proportional to the frequency and inverse value of the field strength. The fit of experimentally obtained dependence by the relation obtained numerically gives the magnetic moment of the ferromagnetic particles. Very interesting observation was made at higher frequencies of the rotating field showing that the filament is going out of the plane of rotating field. Detailed study of this important phenomenon is pending for future publications. Bending modulus of the filament is measured by registering its relaxation to straight configuration from initially prepared deformed shape. Obtained results show that synthesized ferromagnetic filaments are quite stiff and their persistence length has the order of magnitude of several tenth of centimeters.

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