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A simple method to estimate the magnetic moment of magnetic micro-particles

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Abstract

Micro-particles in suspension in a fluid are an example of a very low Reynolds number problem. In this case, no inertial effects are observed. Magnetic micro-particles with magnetic moment m, suspended in a fluid orient to applied external magnetic fields B due to the interaction between the field and the magnetic moment. In this work, we present a simple method to estimate the total magnetic moment of magnetic micro-organisms. The method is based on the application of an external oscillating magnetic field in the sites where the micro-organisms are. In this case, it is possible to obtain theoretically the solution of the equation of motion (rotation of the organism and its trajectory). The solution is a transcendental equation relating the orientation angle and m and can be solved by numerical methods. Changing the frequency and/or the field intensity, it is possible to obtain a situation in which the crystal rotates uninterruptedly (a resonance regime). This condition is related to the applied field intensity, to the frequency, to the medium viscosity, to the crystal dimension, and to the micro-crystal magnetic moment m. The method can be used to estimate the total cellular magnetic moment of magnetic micro-particles.

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1. Introduction

Magnetotactic bacteria are Gram-negative and represent a heterogeneous group of not cultivable prokaryotes. They can be found in coccoid, rod-shaped vibrioid or spirilloid morphologies. All magnetotactic bacteria present an internal organelle, called magnetosome, which produces the chain of magnetic nanoparticles that determines a magnetic moment m of the bacteria (the magnetic moment units are emu or $\mathrm{A\,m^2}$, being $1\,\mathrm{emu} = 10^{-3}\,\mathrm{A\,m^2}$) and is responsible for the magnetic orientation of the bacterial body. The magnetic particles are formed by magnetite (Fe_3O_4) or greigite (Fe_3S_4), depending on the bacteria [1]. One method to estimate the total magnetic moment is called the U-turn method [2]. In this approach, the magnetic moment is determined measuring the U-turn trajectory diameter and the interval of time for re-orientation when the organism is exposed to an instantaneous polarity reversal of the local magnetic field. The U-turn method, however, is not robust. The magnetotactic organism can perform trajectories not necessarily in the optical plane and the time interval is arbitrary (there are no criteria to be used to guarantee that bacteria are truly re-oriented). The U-turn method tends to over estimate m because the measurement of the diameter of the U-turn, or the time of re-orientation is under-estimated (for trajectories out of the optical plane). Using this method, values of m were calculated for several types of non-cultured magnetotactic bacteria, estimating values from 0.3×10^{-15} to $54 \times 10^{-15}\,\mathrm{A\,m^2}$. The first theoretical estimate for the magnetic moment was done counting the contribution of several nanoparticles arranged in a chain. In this way, a magnetic moment of 1.3×10^{-12} emu was obtained, supposing a chain composed of 22 particles of magnetite with volume of $1.25 \times 10^{-16}\,\mathrm{cm^3}$ [3]. The U-turns analysis done by Esquivel and Lins de Barros [2] also supposes that

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bacteria have spherical geometry which it is not always the case. When the bacterium is enlarged, as a small cylinder, another approximation must be done. So, supposing that this small cylinder behaves as a set of attached spheres, the contribution to the total torque can be calculated. Doing the experimental analysis in that way, Bahaj et al. [4] measured the bacterial magnetic moment and obtained $6.1\times10^{-16}\,\mathrm{A\,m^2}$. They also calculated the variation of magnetic moment with the time of growth, and observed that it grows from $2.8\times10^{-16}\,\mathrm{A\,m^2}$ at 35 h to $6.5\times10^{-16}\,\mathrm{A\,m^2}$ at 240 h. Other techniques have been used for measuring the magnetic moment of magnetotactic bacteria. Using a SQUID magnetometer, an average magnetic moment of $1.8\pm0.4\times10^{-12}$ emu had been determined for a bacterium [5]. This technique is interesting because it produces a direct measurement and does not need to suppose unknown values for parameters from the studied cell. Two other interesting ways for measuring the magnetic moment of magnetic bacteria are the analysis of the birefringence arising in a pool of magnetic bacteria in the presence of an external magnetic field [6] and the analysis of the light scattered by a pool of magnetic bacteria [7]. The birefringence transforms an input-linear-polarized light beam into an output elliptically polarized light beam. A phase shift is measured which depends on the intensity of the external magnetic field. Experiments were done with live and dead bacteria. Bacteria were killed with drops of formalin. The measured values for live bacteria, at normal concentration conditions, were about 1.21×10^{-13} emu and for dead bacteria about 1.33×10^{-13} emu. Apparently for dead bacteria, the measured values are higher than for live bacteria. It was assumed that this difference could be an effect of motile behavior in live bacteria. The other technique proposed for measuring the magnetic moment is the analysis of the light scattered by a pool of magnetic bacteria, because the presence of an external magnetic field determines an angular distribution in the orientation of bacteria [7]. This angular distribution affects the structure factor in the scattered-light intensity. With this technique, the average length and average magnetic moment can be determined. For two different culture values of $(2.2\pm0.2)\times10^{-13}$ and $(4.3\pm0.5)\times10^{-13}$ emu were determined.

Another method used to estimate m is related to the trajectory of movement of a magnetotactic bacterium in the presence of a rotating magnetic field vector [8]. In this case, the organism is exposed to a rotating magnetic field and the escape frequency (as well, the field intensity) is measured, giving a better estimate of m. A theoretical analysis of this technique was done in Ref. [9]. The U-turn and rotating field methods, however, depend on the motility of the organism and cannot be used to estimate m of inert particles.

Another proposal will be made in this paper, related to the analysis of the movement of magnetotactic bacteria under magnetic fields of oscillating magnitude. It will be shown that this method can be used to estimate m for inert particles, as well as magnetic particles or dead magnetotactic bacteria.

2. Theoretical analysis

In Ref. [10], the complete problem of the movement of a magnetotactic bacterium under magnetic fields was solved. If the trajectory is not considered, the angular orientation of the magnetotactic bacteria can be found solving the following equation, valid for very low Reynolds number:

$$8\pi\eta R^3\frac{\mathrm{d}\theta}{\mathrm{d}t}=mB(t)\sin\theta \tag{1}$$

where η is the medium viscosity, R is the radius of the bacterium (supposing it is a sphere), m is the magnetic moment, θ is the angle between m and B and $B(t)$ is the magnitude of the magnetic field. If $B(t)=B_0$ is constant, the solution to Eq. (1) is

$$\theta(t)=2\,\mathrm{arctg}\left\{\mathrm{tg}\left(\frac{\theta_0}{2}\right)\exp\left(\frac{t}{\tau_0}\right)\right\} \tag{2}$$

where θ_0 is the angle at $t=0$, $\tau_0=8\pi\eta R^3/mB_0$ is a characteristic time of the process and $0<\theta<\pi$. For a bacterium at $\theta_0\approx0^\circ$, the time to reach $\theta=179^\circ\approx\pi$ is $t=9.5\tau_0$. Now, if $B(t)=B_0\cos(\omega t)$, the solution of Eq. (1) is

$$\theta(t)=2\,\mathrm{arctg}\left\{\mathrm{tg}\left(\frac{\theta_0}{2}\right)\exp\left(\frac{\sin(\omega t)}{\omega\tau_0}\right)\right\} \tag{3}$$

As the sine function has limits ±1, for $(\omega\tau_0)^{-1}\geqslant9.5$ the complete orientation must be observed, and for lower values θ never reach the π value. So, the determination of the threshold $(\omega\tau_0)^{-1}=9.5$ is important to determine the value of m. If the oscillation period of $B(t)$ is τ, then the threshold can be written as

$$\frac{\tau}{\tau_0}\approx60 \tag{4}$$

From Eq. (4) it can be concluded that, for $\tau>60\tau_0$ the particle orients to the magnetic field direction, stays in this direction for a while before it reorients to the new direction of the magnetic field after the beginning of a new period. For $\tau<60\tau_0$ the particle does not orient completely to the magnetic field direction, staying in a continuous oscillation but never reaching angles near to 180°. For the case of $\tau\approx60\tau_0$ it must be observed that the particle oscillates continuously between θ_0 and $\pi-\theta_0$.

Fig. 1 shows this behavior. In this case, the following parameters were used to simulate the curves using Eq. (3): $B_0=3\,\mathrm{G}$, $\eta=0.01\,\mathrm{P}$, $m=10^{-10}$ emu, $R=3\,\mu\mathrm{m}$, $\theta_0=0.1$ rad, $\omega=5.5$ rad/s (continuous line), $\omega=4.5$ rad/s (dotted line) and $\omega=6$ rad/s (dash-dotted line). Those parameters produce the indicated ratios τ/τ_0 at Fig. 1.

But, as bacteria are self-propelled beings, the trajectory followed by it must be analyzed, as the angular orientation is difficult to observe experimentally in live bacteria. The equations for the trajectory can be obtained in simple form for the case of magnetotactic bacteria with an integer number of turns in the flagella [10]. If the sine function is changed to a square wave function, the solution with $B(t)=$ constant can be used for $0<t<\tau/2$, where τ is the

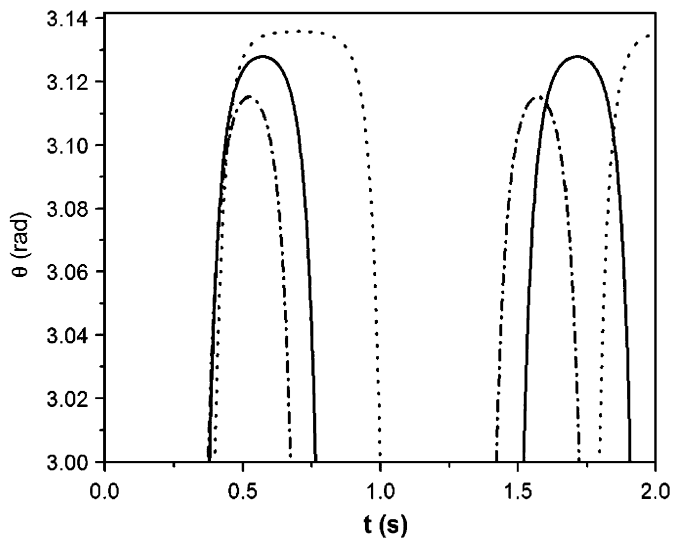

Fig. 1. Orientation angle as function of time as described by Eq. (3). The continuous line corresponds with $\tau/\tau_0 = 57$, dotted line with $\tau/\tau_0 = 70$ and dash-dotted line with $\tau/\tau_0 = 52$.

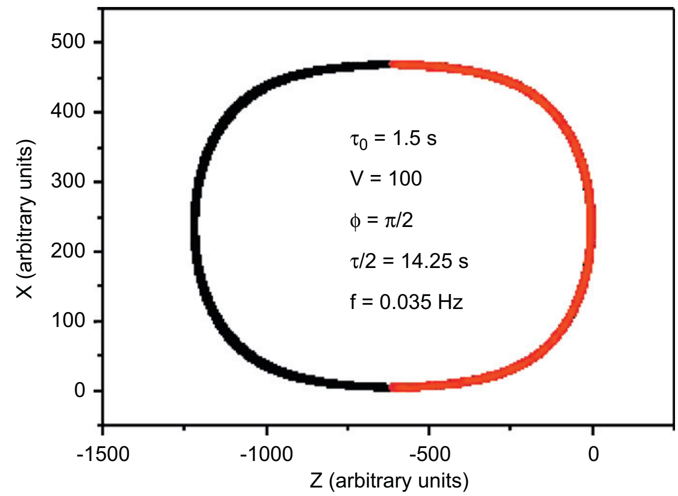

Fig. 2. Magnetotactic bacterium trajectory simulated using Eqs. (2, 8 and 9) and the parameters inside the graph.

period of the square wave. In this case, the trajectory equations in the XZ plane are

$$\dot{\theta} = \frac{\sin\theta}{\tau_0} \tag{5}$$

$$\dot{x} = v \sin\phi \sin\theta \tag{6}$$

$$\dot{z} = v\cos\theta \tag{7}$$

where v is the velocity generated by the flagellar propulsive force and ϕ is one Eulerian angle and it is constant in this case [10]. The solution for the trajectory is

$$x = (\tau_0 v \sin\phi)\theta + x_0 \tag{8}$$

$$z = (v\tau_0)\ln(\sin\theta) + z_0 \tag{9}$$

Eqs. (2, 8 and 9) at $0<t<\tau/2$ describe the trajectory followed by the magnetotactic bacterium. The change of frequency in the square wave results in the change of the time interval. A complete trajectory is formed joining the two trajectories for $0<t<\tau/2$ and $\tau/2<t<\tau$. Fig. 2 shows the result for a simulated trajectory using the last equations in a complete square wave period. The case analyzed in Fig. 2 corresponds with $\tau/2 = 9.5\tau_0$, and the curve observed has reflexion symmetry.

Experimentally the formation of circular trajectories in threshold frequencies is observed, with ellipsoidal trajectories for lower frequencies and diffuse trajectories for higher frequencies than the threshold frequency. More detailed analyses of video-microscopy of magnetotactic bacteria trajectories will be reported elsewhere.

Interestingly, Eqs. (8 and 9) are valid only for live magnetotactic bacteria. But Eqs. (2 and 3) can be used to analyze the response to oscillating magnetic fields of magnetic particles or dead magnetotactic bacteria. As these equations are the solution for $\theta(t)$, the condition $(\omega\tau_0)^{-1} = 9.5$ corresponds with a kind of resonance regime, because the oscillating period is the sufficient to re-orient the particle and after that it immediately starts its return, creating a continuous circular movement. The U-turn and the rotating magnetic field vector methods [2,8,9] cannot be used to analyze magnetic particles or dead magnetotactic bacteria, because they were developed considering that bacteria are self-propelled. In considering symmetries different from spherical, the expression for τ_0 must change to another form factor in the numerator of the fraction. A more detailed experimental analysis will be reported elsewhere with ferrofluid particles.

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