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New approaches in the design of magnetic tweezers–current magnetic tweezers

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ABSTRACT

The main advantages of the magnetic tweezers are the low price and simplicity of use. However the range of their application is reduced due to shortcomings like, for example, the remanent induction of the core and interaction between ferromagnetic cores.

We present the new design of magnetic tweezers–Current Magnetic Tweezers (CMT) that allow particle manipulation by means of the magnetic field generated by the electric currents flowing through the non-magnetic wires. Arranging wires in different geometric shapes allows the particle movement either in two or three dimensions.

Forces acting on the magnetic particles with the magnetic moment of $2 \cdot 10^{-11}$ A m^2 at distances up to 1 mm had been experimentally measured. It is established that a current of about 1 A at a 1 mm distance generates force of (approximately) 3 pN which is consistent with theoretical estimates.

1. Introduction

Advances in nanotechnology gave rise to the growing interest in the study of methods of manipulation of micro and nano-objects. The main attention is focused on the following systems: optical tweezers [1], atomic force microscope (AFM) [2] and magnetic tweezers [3–5]. Each of them provides unique opportunities to study micro objects, including their mechanical properties (behavior under the influence of tension and/or torsion forces). These forces are applied either AFM, or by means of external electromagnetic field manipulators (optical tweezers and magnetic tweezers). Let us present a brief overview of the principles of listed above methods. To manipulate a single molecule, one end of the molecule is attached to a magnetic microparticle (in the case of magnetic and optical tweezers) [6] or to the AFM cantilever [7]. The other end is then attached to the surface of a coverslip. Once the molecule is attached one can carry out the experiments and study its mechanical properties. These “single-molecule” methods are very sensitive, they allow to measure the displacement of the object down to nanometers and apply forces in the order of piconewtons. On one hand, all of the above methods are based on the same principles, on the other hand, each technique can be used to perform unique operations that are not possible with the others. Still, all these methods have limits to their application. Optical tweezers are used only for partially transparent particles. The size of such particle has to be between 0.2 and 5 μm (it cannot be smaller than the half (quarter) of the visible light or bigger than a few wavelengths). Optical tweezers manipulate objects in liquid environment [8,9]. AFM allows to manipulate atom-sized objects and observe objects up to several nanometers in size. With the help of the AFM the sample surface can be scanned and small atomic clusters can be moved. However, this method is not suitable for manipulating objects bigger than several hundred atoms [3]. Magnetic tweezers have various designs and are used to work with large organic molecules like DNA and RNA. They provide opportunities to study elastic properties of DNA and dynamic properties of various biological macromolecules, for example, polymerases, helicases, topoisomerases, DNA-binding proteins [10]. In comparison with other micro-tweezers magnetic tweezers have a number of advantages: there are no restrictions on transparency and the size of particles (unlike optical tweezers) and they can work in various environments: gas, liquid, vacuum. [4]. In general, magnetic tweezers consist of the ferromagnetic cores magnetized with winded coils. However, the presence of ferromagnetic cores in existing models of magnetic tweezers causes two serious drawbacks:

1. presence of a remanent magnetic field of the core means the magnetic particle is affected by this field and the effect cannot be canceled by merely switching off the electric current in the coils;

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2. magnetization of any of the cores will cause induced magnetization of the other cores of the magnetic tweezers. Thus, working area of the magnetic tweezers as well as range of the effects they produce is limited.

To overcome these drawbacks, we suggest a method of manipulating magnetic particles that uses magnetic field from currents flowing through nonmagnetic wires. We call them Current Magnetic Tweezers (CMT) and going to proceed to discuss in more detail their design and operation.

2. Method

2.1. CMT concept

CMT manipulates particles through the magnetic field from an electric current flowing through nonmagnetic wires (conductors). Fig. 1 shows the configuration of magnetic fields in the area between two conductors. The current in the top conductor creates the gradient magnetic field which attracts the magnetic particle toward the conductor axis (Fig. 1a). The particle's magnetic moment aligns with the direction of the magnetic field (white arrow inside blue sphere) and the particle moves in the direction of the field high gradient – toward the conductor. If electric current is turned off, the particle stops moving but retains the orientation of its magnetic moment. With time magnetic moment can change due to effect of thermal fluctuations (Fig. 1b). When the current is passing through the lower wire, the particle's magnetic moment aligns with the field of the lower wire and starts moving toward it. (Fig. 1c). The force applied to the particle can be controlled by changing the value of the electric current. Orientation of the applied force can be changed by passing electric current through different conductor.

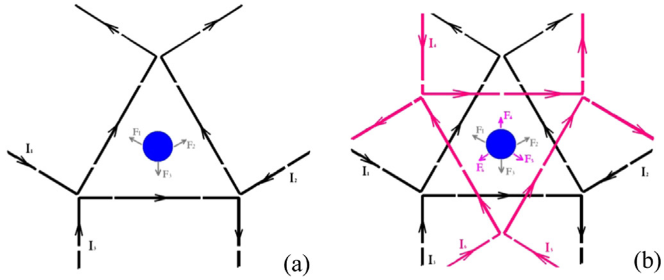

Fig. 1. Diagram of the particle movement between two non-magnetic conductors. (a) Particle movement under the influence of the gradient magnetic field created by the current I_2. (b) The position of the particle without current in either conductor (orientation of the moment changes as a result of thermal fluctuations). (c) Particle movement under the influence of the gradient field created by the current I_1. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

To be able to apply force in any direction within the XY plane the system has to include at least three conductors. We started with conductors arranged in single-layer "triangle" geometry (Fig. 2a). The double-layer system allows the particle movement in the XYZ space (Fig. 2b).

This design eliminates the main drawbacks present in magnetic tweezers with the ferromagnetic core, but it has its own disadvantages:

- the required currents are high, they heat the conductors that in turn leads to heating of the work area;

- to produce high currents large conductors are required.

Consequently, we are forced to choose between the size of the working area and the strength of the created forces. However, other designs of micro-tweezers experience similar difficulties.

2.2. Numerical evaluation

To estimate CMT characteristics we performed the numerical evaluation of the force applied to magnetic particle and the speed gained by the particle in liquid under the influence of the gradient magnetic field. To calculate the force, consider magnetic particle with a diameter $d_{part}=5\ \mu\text{m}$ and a saturation magnetization $I_{part}=300{\cdot}10^3$ A/m near the micro-wire of the radius $R_{wire}=15\ \mu\text{m}$. The particle volume is $V_{part}=\frac{1}{6}\pi d_{part}^3=6.5{\bullet}10^{-17}\ \text{m}^3$ so its magnetic moment equals: $M_{part}=I_{part}V_{part}=2{\cdot}10^{-11}\ \text{A m}^2$.

Considering that the induction of the magnetic field of the micro-wire is given by$B_w=M_{part}\frac{\mu_0}{4\pi}\frac{2I}{r}$, where I is the current through the wire, $\mu_0=1.26{\bullet}10^{-6}\text{N/A}^2$ is the magnetic constant, and r is the distance between the particle and the wire. The acting force is:

$$F=M_{part}\frac{\partial}{\partial r}B_w=M_{part}\frac{\mu_0}{4\pi}\frac{2I}{r^2}=4{\bullet}10^{-6}{\bullet}\frac{I}{r^2}[pN] \tag{1}$$

Fig. 3 shows the force exerted on magnetic particle depending on the distance between the particle and the wire. At the distance of about 100 μm the force can reach the value of 10^3 pN. But at the distances about 1000 μm the force falls to the single units of pN.

To calculate the speed of the particle the Stokes' law is used. Stokes established that at low speeds (i.e. at small values of Reynolds number (Re)) the resisting force on a particle moving through the liquid is proportional to the coefficient of the dynamic viscosity η, the characteristic size of a body r_{part} and the velocity of the ball υ. In general the coefficient of proportionality depends on a shape of a body but for a sphere the coefficient of proportionality equals 6π and if we assume that magnetic particle is a sphere with radius r_{part}=2.5μm then, according to Stokes' formula, the frictional force is:

$$F=6\pi r_{part}\eta\nu \tag{2}$$

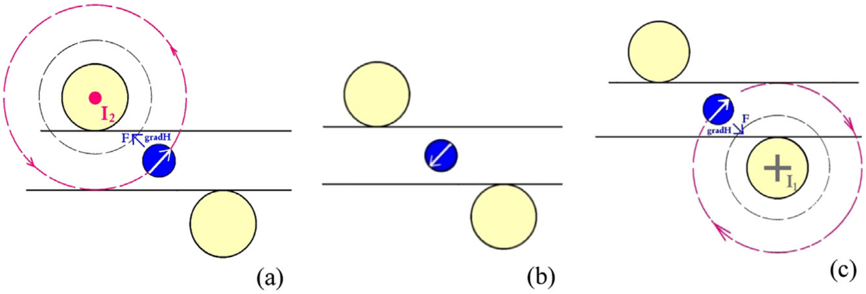

Fig. 2. CMT diagram. (a) Single-layer system allows particle movement in three directions on a plane. (b) Double-layer system allows the particle movement in the volume. The first layer – black lines, the second layer – pink lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)