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Application of conical magnetic rotating fields for controlled colloidal self-assembly

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Abstract. Tunable interactions under the influence of external electric and magnetic fields open the way to controlled transport and self-organization in model and living systems. In this paper, we establish new experimental system parameters for tuning interparticle interactions in colloidal systems using a three-dimensional precessing conical magnetic field. The paper presents a digital twin of the experimental setup, simulation of electromagnetic fields in order to find the optimal self-assembly parameters. The results of pilot experiments with magnetic particles of silicon dioxide 2.47 μm in size in deionized water are demonstrated, the phenomenon of controlled self-assembly is shown.

Keywords: soft matter, self-assembly, magnetic fields, colloids

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Материалы конференции
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Применение конических магнитных вращающихся полей для управляемой коллоидной самосборки

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Аннотация. Управляемые взаимодействия под действием внешних электрических и магнитных полей открывают путь к управляемому транспорту и самоорганизации в модельных и живых системах. В этой статье мы устанавливаем параметры новой экспериментальной системы для управления межчастичным взаимодействием в коллоидных системах с использованием трехмерного вращающегося конического магнитного поля. В работе представлен цифровой двойник экспериментальной установки, симуляции электромагнитных полей с целью поиска оптимальных параметров самосборки. Приведены результаты пилотных экспериментов с магнитными частицами диоксида кремния размером 2,47 мкм в деионизированной воде, показано явление управляемой самосборки.

Ключевые слова: мягкая материя, самосборка, магнитные поля, коллоиды

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Introduction

Systems with tunable interactions [1] represent a promising class of model systems that are important for fundamental and applied research. Tunable interactions directed by external electric [2–7] or magnetic field [8–15] play a major role in many fields of colloidal matter, such as phase transitions [10, 16–19], collective dynamics [20, 21], guided transport in colloidal [22–24] and living [25–27] systems and pattern formation [28, 29].

Of particular interest is the formation of condensed phases from colloidal suspensions in a precessing multi-axial magnetic field [11]. By varying the precessing angle of the 3D conical fields, we get different colloidal patterns. It is known that at magic angle 54.7° [30, 31], interactions become spatially isotropic being attractive or repulsive depending on particle and solvent permittivity. In fact, such an interaction should lead to the appearance of equilibrium micro-phases; however, to date the issue of tunable interactions across magic spatial hodographs in colloids has not been well studied.

Moreover, multi-axial rotating magnetic field is a promising tool for additive manufacturing, especially 3D printing, and for obtaining new materials. To address these issues, we have performed numerical simulations of multi-axial rotating magnetic field and developed three-dimensional magnetic setup to examine dynamics of colloidal and living systems at different precessing angles of external rotating magnetic field.

Materials and Methods

At the stage of setup creation, an extremely important step is design and optimization of experimental setup parameters and geometric features using an experimental setup digital twin.

In fact, the goal was to achieve a magnetic field with strength of the order of H ≈ 100 Oe and homogeneity 99% at the center with a square of 2.5 mm. In addition, due to the fact that the objective of the microscope must fit close enough to the sample under study, we designed a coil frame through the center of which the microscope passes.

The digital twin shown in Fig. 1 consists of four multilayer coils on a magnetic core in a horizontal plane and two vertical coils on a frame. A sinusoidal current is applied to the winding, which gives rise to the appearance of a rotating magnetic field. The test sample, placed on a glass substrate, is illuminated by an external light source. The image is digitized using a microscope objective, an infinity-corrected objective and a CCD camera.

Using the Finite Element Method (FEM), a numerical model of the experimental setup was created. Breaking our three-dimensional model into a finite number of subdomains, we solve the equations of electromagnetism:

$$\nabla\times H = J \tag{1}$$
$$\nabla\times A = B \tag{2}$$
$$J = \sigma E + J_e \tag{3}$$

with boundary condition $n\times \mathrm{A} = 0$.

In fact, the use of a high permeability core greatly influences the *B*–*H* curve and the intensity of the magnetic field. The relationship between magnetic induction and magnetic field strength through magnetic permeability is introduced as:

$$B = \mu H \tag{4}$$

It is more convenient to use the dimensionless relative magnetic permeability $\mu_r = \mu/\mu_0$. It is known that the relative magnetic permeability is related to the susceptibility through the relationship $\mu_r = 1+4\pi\chi$. The magnetic permeability depends on the properties of the substance and, as in our case, for anisotropic substances, on the magnitude and direction of the magnetic field.

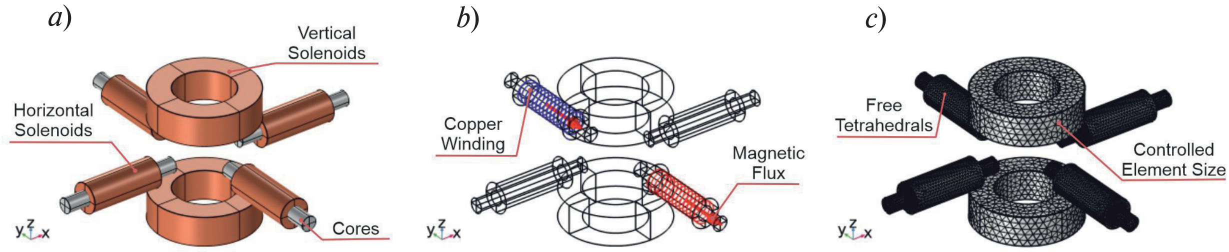

Fig. 1. Experimental setup digital twin: an external view of the installation, horizontal core solenoids and vertical solenoids (*a*), a consideration of copper winding for the direction of the magnetic induction vector (*b*), a decomposition of the 3D model into finite elements (*c*)

We considered a few variants of cores and the most convenient one turned out to be a ferrite core with a relative magnetic permeability $\mu_r = 400$.

To create a more intense magnetic field, it is much more rational to use multilayer coils. It is known that the inductance of a multilayer coil on a core is calculated by the equation,

$$L = \frac{\mu_0 \mu_r \cdot S_c \cdot N^2}{l_{avg}} \tag{5}$$

where $\mu_0 = 4\pi \cdot 10^7$ H/m, μ_r is the relative permeability, S_c is the cross-sectional area of the magnetic circuit, N is the number of turns, l_{avg} is the average length of the magnetic field line.

From the Eq. 5 it can be seen that the inductance depends quadratically on the number of turns and linearly on the magnetic permeability.

Using a copper wire with $d = 0.5$ mm and a frame with a long winding $l = 19$ mm, taking into account the insulation, we got $N \approx 1200$ turns, consisting of 36 layers. The inductance of such a coil is $L \approx 67.8$ mH.

The homogenized multi-layer circular coils used numerically, shown in Fig. 1, make it possible to vary the current strength, the number of turns and the distance between the coils to achieve a uniform magnetic field profile of the desired strength.

In fact, differences in the inductances of the coils are compensated by changing the distance between them, which makes it possible to create unique conic fields.

The vertical coils in the final winding consist of 40 turns and 30 layers ($N = 1200$), and the horizontal coils of 100 turns and 10 layers ($N = 1000$). Both coils are wound with copper wire with a diameter of $d_w = 0.5$ mm and a conductivity of $\sigma = 10^6$ S/m. The winding is supplied with an alternating current with a power of $I = 1$ A with a frequency of $\nu_0 = 1–20$ Hz.

As a pilot experiment we examined a system of magnetic particles of silicon dioxide 2.47 μm in size in deionized water.

Results and discussion

As a numerical solution result of Eq. 1—3, we obtained the field distributions in three different operating modes shown in Fig. 2. The setup allows one to work with both two-dimensional and three-dimensional rotating magnetic fields. The intensity of the magnetic field in the center is controlled by the strength of the current supplied to the coil windings and varies from 0 to 170 Oe. The independence of the vertical and horizontal coils makes it possible to control the precession angle of the conical field by adjusting the current strength on the planar and vertical coils.

The results of pilot experiments are demonstrated in Fig. 3. In multi-axial regime there is a colloidal system exhibiting precessing in a magnetic field with spatial hodograph at a conical angle θ.

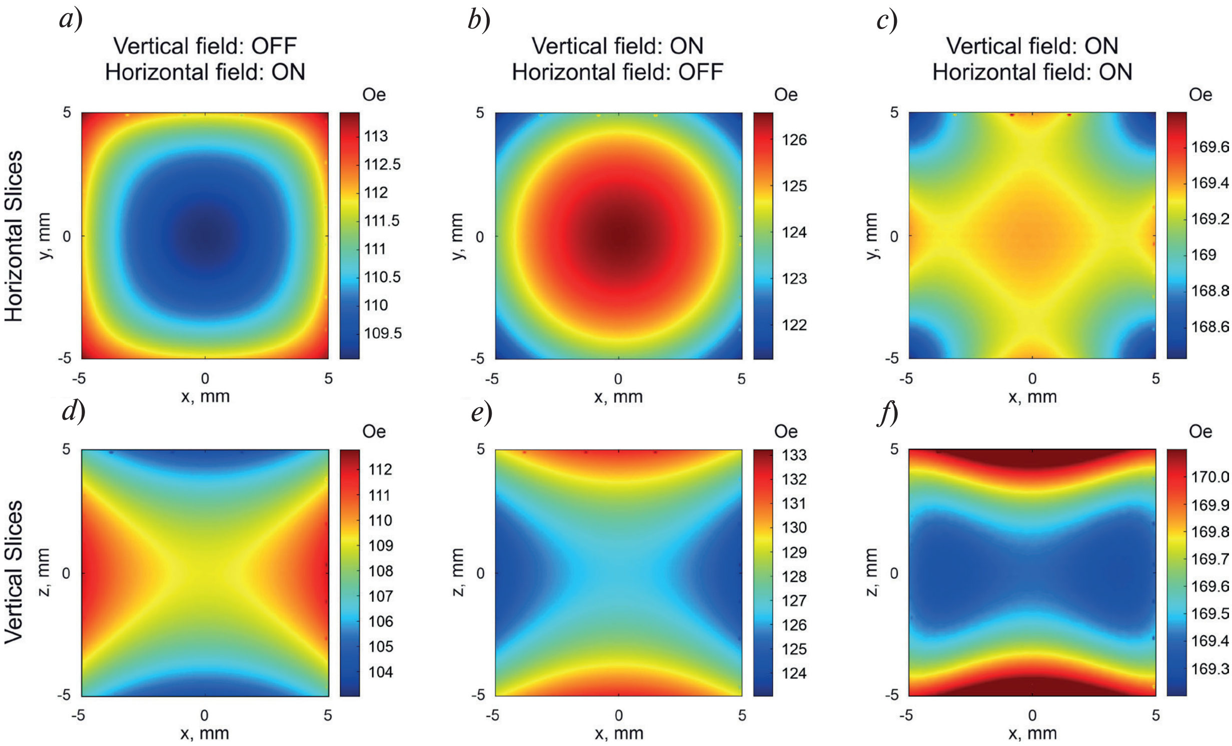

Fig. 2. Numerical simulation of magnetic fields in three operating modes (averaged period): electric field strength slices in horizontal plane (*a*, *b*, *c*); electric field strength slices in vertical plane (*d*, *e*, *f*)

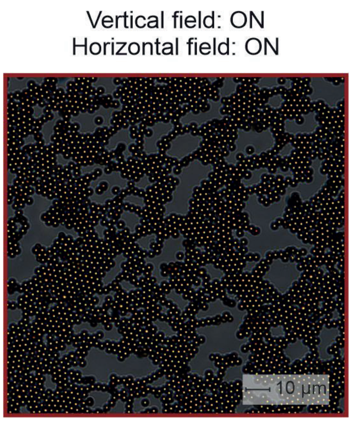

Fig. 3. Experimental snapshot of colloidal system: pilot experiments in horizontal and vertical fields simultaneously

Conclusion

As we mentioned before, we are able to control the conical angle and systems precessing at different conical and magical angles which is also a good testbed for prospective studies.

As a result, by creating a digital twin of the experimental setup, we were able to design the optimal geometry and select the appropriate parameters for vertical and planar coils. This step is important in terms of creating new equipment for observing various phenomena in the field of soft matter physics and general condensed matter phenomena. By carrying out pilot experiments, we proved the possibility of self-assembly of colloidal structures into aggregates.

In addition, this setup can be used to carry out promising studies in the field of targeted drug delivery, 3D printing and other applications in the field of colloidal and living matter.

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