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Investigation of ferrofluids motion in multi-pole electromagnetic field

K. Šileika, I. Skiedraitė

Department of Mechatronics, Faculty of Mechanics and Mechatronics,
Kęstučio g. 27-319, 44312 Kaunas, LITHUANIA,
Phone: +370 37 300902, E-mail: karolis.sileika@gmail.com, inga.skiedraite@ktu.lt.

Abstract

Experimental data on magnetic induction in several points between two solenoids, closely placed in a row, was obtained. The results helped to understand the necessary polarity sequence of a row of electromagnets in order to effectively control the flow of FF between at least two active solenoids. Further on, a prototype for cleaning of clots in human vascular system, utilizing FF and ultrasound catheter, is proposed.

Keywords: ferrofluids (FF), ultrasound catheter, solenoids, cleaning of clots, electromagnets

Introduction

Ferrofluids were originally discovered in the 1960's at the NASA Research Center, where scientists were investigating different possible methods of controlling liquids in space [1]. The benefits of a magnetic fluid were immediately obvious: the location of the fluid could be precisely controlled through the application of a magnetic field, and the fluids could be forced to flow by varying the strength of this field.

For the last thirty years, ferrofluids with superparamagnetic properties have had significant interest in the biomedical field [2]. These ferrofluids exhibit characteristics similar to paramagnetic materials except that their magnetization in low to moderate fields is much larger. Due to these characteristics, research is being done on the use of these ferrofluids as a method to carry drugs to targeted locations within the human body using external magnets as the driving force [3].

A ferrofluid is properly classified as a stable colloidal suspension, composed of very small particles of magnetite suspended in a liquid medium. Each particle is coated with a stabilizing agent, usually a synthetic hydrocarbon, to prevent them from clumping together when they are exposed to a magnetic field. In spite of the name, ferrofluids are not themselves magnetic, but only display magnetic properties when they are in the presence of a strong magnetic field.

Ferrofluids are one of many applications of nanotechnology – a branch of science that deals with particles the size of atoms and molecules. The average size of a ferrofluid particle is about 100 Angstroms, or 10 nanometers. This is smaller than a magnetic domain [4].

Ferrofluids have many uses industrially and medically. They are used in audio speakers to improve transmission, and also to detect domain structures in magnetic tapes, CD's and floppy disks, as well as metal alloys, garnets, steel alloys and geological rocks. They can detect defects in magnetic recording media as well as very tiny flaws in steel. Ferrofluids can be combined with a liquid polymer to create magnetic plastic. They enable be easily reclaimed and recycled in the environment due to their high density and magnetic properties [4].

In this paper the results of ferrofluids motion investigation in multi-pole electromagnetic field are presented.

An object of this investigation are the ferrofluid's electromagnetic properties, when fluid is subjected to the electromagnetic field, generated by two solenoids. Ferrofluids, consisting of surfactant coated magnetic nanoparticles with the diameter ranging from 1 to 100 nm in a liquid host (carrier fluid, which forms a stable colloidal suspension) were used in experiment.

Magnetic properties of ferrofluids

A typical ferrofluid (FF) has only 5% of magnetic particles in volume, 10% of surfactant in volume [5] and the rest is the carrier liquid. The particles are coated with a surfactant that disperses the particles and prevents agglomeration by overcoming the local magnetic fields and van der Waals forces that exist between particles. As a result, when the ferrofluid is not in the presence of an external magnetic field it has no net magnetization. However, when a magnetic field is applied to the solution, the particles are spontaneously oriented with respect to and along the magnetic flux lines. When the magnetic field is removed, the particles will disperse randomizing their orientation and establishing a state of no net magnetization. Since the FF is sensitive to external fields, the particles can be positioned and controlled by magnetic fields with the forces holding the particles in place proportional to the applied field strength and the magnetization of the particles.

When the paramagnetic liquid is subjected to a sufficiently strong magnetic field, which is normal to FF surface, then FF tend to mass in characteristic way by forming liquid spikes (Fig. 1). This is happening due to particles tendency to align in the direction of magnetic field lines [6]; this effect is called normal field instability. The formation of such structures increases the surface free energy together with gravitational energy but decreases magnetic energy. It is easy to understand, that FF surface free energy reaction occurs only in the locations where magnetic field has a critical strength [7], although the height of the spikes is [6] restricted by the tension of the liquid's surface.

This property, in case of closed environment like a circular cavity, creates an energy concentration zones between the cavity's surface and nanoparticles (Fig. 2). Instead of even-spread volume of FF, with a low energy interaction, along the constraining surface of the cavity, it is possible to get some magnetic energy concentration zones with the increased surface to surface interaction intensity, which can lead to abrasive interaction.

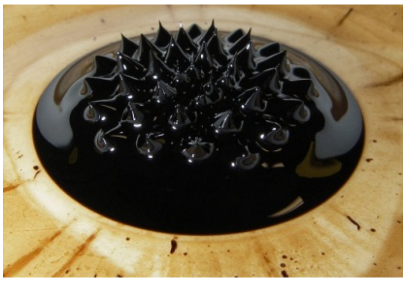


Fig.1. **FF reaction to magnetic field [8]**

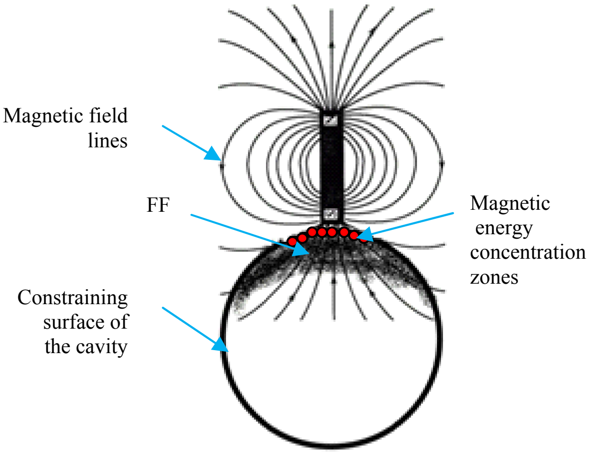


Fig.2. **FF in a circular cavity under influence of magnetic field**

Because each FF's particle in a magnetic field acts as a magnetic dipole, it tends to form structures along magnetic lines, which increases the liquids viscosity. The denser the packing of the formed structures, the more viscous the FF is. This property contributes greatly to the flow control off FF- it is easier to achieve the necessary velocity of the travelling agglomerate in the carrier liquid, together accumulating a grater kinetic energy.

Experimental setup for investigation of FF behavior

An experiment was carried out in order to investigate the behavior of FF flow under the influence of an electromagnetic field, or to be more precise, controlled displacement of FF using the electromagnetic field similar (in behavior) to a phenomenon of a traveling electromagnetic wave. To create conditions similar to the traveling electromagnetic wave two solenoids were used (Fig.3). Both were wound on an interconnected core, using a 0,12 mm diameter copper wire. Each solenoid was made of 200 windings. Because it was handmade, some mismatches in solenoids' dimensions occurred, but it didn't influence the results.

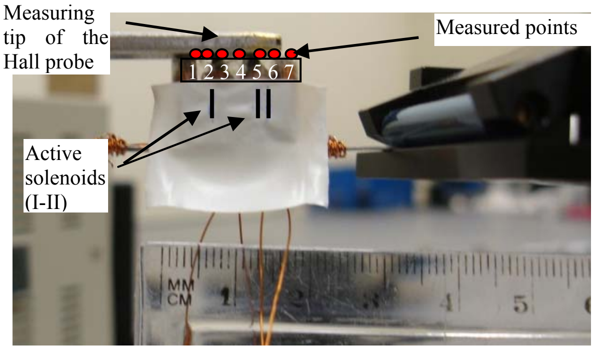
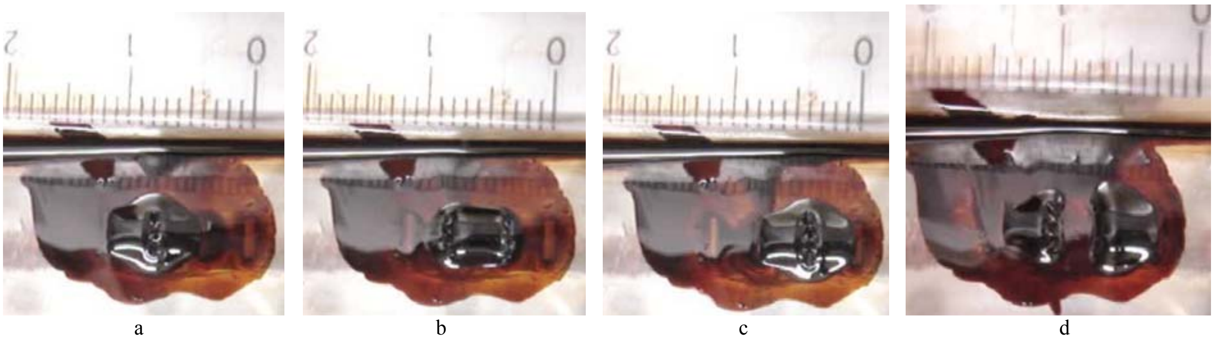


Fig.3. **Solenoids with a tip of the Hall probe**



a b c d

Fig.4. **Powering of solenoids: a - middle left solenoid is active; b - both middle solenoids are active; c - middle right solenoid is active; d - different polarity of solenoids then in a-c cases**

Solenoids were activated by a two channel DC power supply. The electromagnetic field at seven points (presented in Fig.3 by red dots) was measured with the help of a magnetometer (Hall probe Ш1-8), along the line between the first and the last points. Measurements were done with only two middle solenoids, but it was sufficient to create a model of arrangement of the electromagnets in order to achieve a travelling electromagnetic wave. The obtained results will be discussed in the following chapter.

After establishing the required polarity sequence of the used solenoids, the setup was changed to achieve the controlled flow of FF. In Fig. 4, a-c powering of solenoids is shown in the following sequence: a- middle left → b- middle left and middle right → c- only middle right. The polarity was S-N on the tops of electromagnets. During the measurements it was found, that this sequence of polarity ensures best mobility of FF blob between two electromagnets. In Fig. 4, d solenoids were powered, at the same time, so they would have S-S polarity on the same plane. It is evident, with respect to flow smoothness between the poles, that first case (S-N polarity at the peaks of solenoids) results are more satisfying.

The magnetic field, produced by both solenoids was weak, because the solenoids were interconnected by their cores. The magnetic field could be stronger if the solenoids were separated by an isolator.

Concerning the results, the polarity of solenoids peaks must differ in order to get a smooth transition and a pole-like zone in the area between two active poles. This will ensure, that when FF is dragged along a circumference path (plane of path is vertical or horizontal) the fluid will follow the travelling magnetic field more precisely compared to the case when polarity at the peaks of solenoids is the same. It is important when the distance between electromagnets will exceed the effective distance for a continuous flow of FF.

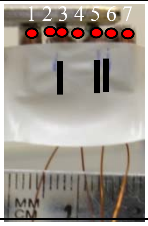
Obtained results

The measurements of solenoids' generated electromagnetic field were performed, in order to find the best sequence to power them in order to achieve the most effective FF control. Electromagnets were made of electromechanical steel cores, welded together at the bottom parts, and copper wire, 200 windings per solenoid. Each solenoid was ~5mm wide and centers of each core were separated by 5mm. Some air gap, ~1 mm, was present between all solenoids.

In Table 1 and Table 2 experiment results are given. The measurements were performed with 2 different polarity sequences with the magnetometer's measuring tip above poles at the distance of ~1mm, at 7 measurements points.

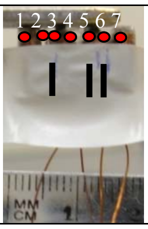
The accuracy of numerical values of the obtained results is sufficient to see the distribution of the values of a magnetic induction along all measured points, which gives a good representation of the necessary polarization sequence of several electromagnets placed in a row.

Table 1

Measurement position	Representation of positions	Polarity sequence*	Electric current, A	Magnetic induction, T
1		S N S N S N S N	1	0,0026
2				0,0091
3				0,0234
4				0,0086
5				0,0216
6				0,0080
7				0,0030

*Polarity sequence is given for four poles, because two active solenoids reside in between two inactive solenoids, which have interconnected cores.

Table 2

Measurement position	Representation of positions	Polarity sequence*	Electric current, A	Magnetic induction, T
1		N S S N S N N S	1	0,0044
2				0,0067
3				0,0187
4				0,0121
5				0,0167
6				0,0057
7				0,0048

Design of the magnetic field generator

The proposed device, shown in Fig.5, is designed to control the flow of ferrofluids (FF) in a closed space with the purpose of increasing the efficiency and reliability of cleaning of clots in human vascular system.

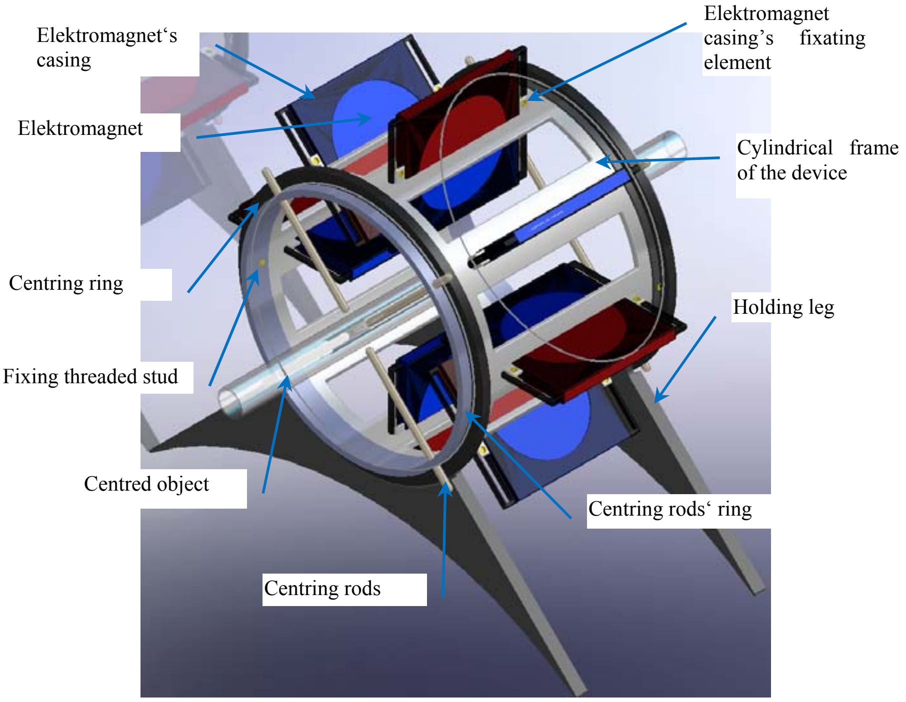


Fig.5. **3D model of the device for cleaning of clots in human vascular system**

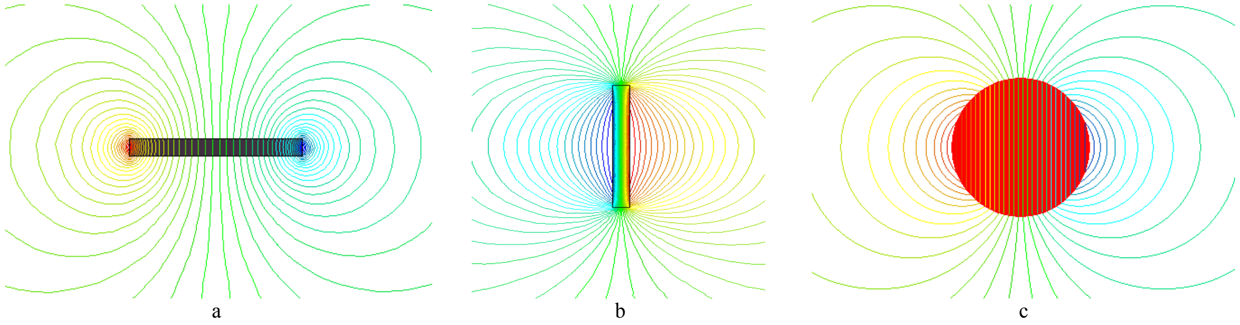

a b c

Fig.6. **Magnetic field concentration lines depending on the shape of magnet: a - side view of a square magnet with poles on the sides of the magnet; b - side view of a rectangular magnet (short end-edges) with poles on the ends of the magnet; c - ball-shaped magnet [9]**

The device must create a traveling electromagnetic wave in order to induce a flow of a certain volume of FF, which is injected into the cleaning zone of a closed space. The running wave then drives the FF in a circular manner thus creating an abrasive effect in the contact zone of nanoparticles of FF and clot material on the wall of a blood vessel.

To create the traveling electromagnetic wave should be used at least three electromagnets, which have to be placed in special casings. The casings, in a circular way, are inserted into the slots of the main cylindrical frame of a device. The shape of electromagnets is chosen such as shown in Fig. 6 a because it has a long magnetic flux-front line, along which FF will tend to distribute itself, compared to flux-front lines produced by magnets with shapes represented in Fig.6 b and c. The narrow area from the front-line of the magnetic field of one side to the front-line of another side is formed between two electromagnetics, thus the control of the FF flow from one electromagnet to another one is simplified.

The investigated object will be centered and fixed with centering rods, after it is placed into the opening in the device. The rods are lowered all at once on each side of the device. In order to do so, based on principle of clamping force, the transmitting system centering ring and centering rods will be mated in that manner.

The necessary position of the casings of electromagnets after lowering them is fixed with fixing screws on both sides of the casings. Each casing can be lowered individually to fit the shape of the fixed object. The closer the electromagnets will be fixed to the cleaning zone, the weaker the electromagnetic field will be needed for individual magnets.

The device will be lightweight, because the majority of elements, except the electromagnets, are going to be made from plastic material. Considering the device's dimensions, mounting it on an object like human arm or leg will be simple. In case when device will be required to be stationed on a firm base, holding legs can be provided.

Device for cleaning of clots in human vascular system

Some main aspects for future development of the device for cleaning of clots have to be taken in consideration:

- Nanoparticles should be dispersed in a target liquid filled cavity, creating FF with applied alternating magnetic field (with dynamically controlled magnets);
- The control of particles must be sufficient to the extent that all particles present in the target area are suspended for induction of vibration acceleration using the ultrasound catheter;
- Permanent magnets are not suitable, because particles need to be pushed/dragged in a controlled manner, avoid creating blob of fluid with undesirably high viscosity, thus electromagnets have to be used for convenient switching on/off of the magnets and creating the driving force;
- The control of electromagnets and vibration of the ultrasound catheter has to be co-controlled, in order to ensure that the vibration frequency in adequate for the target Fe-based nanoparticles.

According to the research paper [3] in-one-plain arrangement of electromagnets has a better control over particles, but has a limited approach distance due to size of magnets and its arrangement. When magnets are arranged in several planes, then lower precision on particle movement was achieved due to the decreased number of magnets per plane. Limitations in both arrangements can be bypassed by:

- using smaller magnets, thus increasing their number per plane;
- using magnets of odd shapes like cone [3].

Taking in account the above mentioned aspects the proposed device under considerations is shown in Fig. 7. There the nanoparticles are delivered to the target area in the catheters tip (inside of the coil shaped tip) using magnetic field to hold them inside. Further the particles are allowed to disperse via controlled action of the electromagnet. Dispersed particles will form a sort of ferrofluid-like medium in the definite volume.

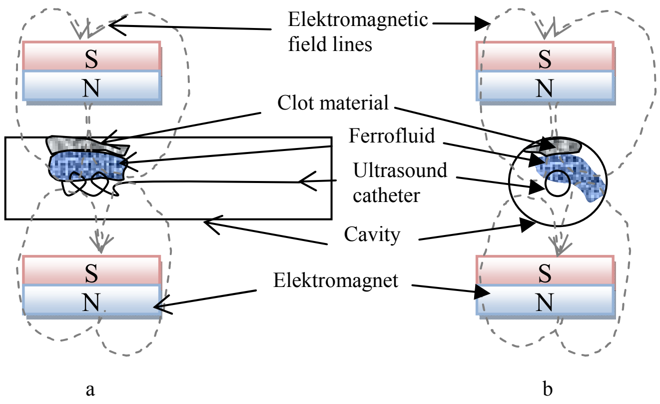


Fig. 7. **System under consideration a - side view; b - front view**

In the initial phase of development of magnetically controlled particles and the ultrasound catheter, the number of electromagnets, their strength, size, orientation, etc. has to be determined experimentally. Induced vibration by the catheter will be transmitted to nanoparticles enabling them to destroy present clot more precisely. The clot material will be captivated in the medium until it is broken up to a needed, harmless size. As particles are of nanosize, they can be left to float in the system, unless it is specified otherwise.

Conclusions and suggestions

1. In the presented paper the experimental setup for determining the best polarity sequence of more than one solenoid in a row for purpose of control of FF flow is discussed.
2. Measurements of electromagnetic field were done, which showed that in order to effectively control the flow of FF the electromagnets have to be powered in a manner that would create polarity sequence represented in Table 1. Doing so, an additional strong "pole" above the air gap between two solenoids is created.
3. After carrying out experiments a model of the electromagnetic field generator was designed for use in the system for cleaning of clots in small cavities.
4. Also stronger magnets will be designed (size, shape, number of windings, core material), to fit the prototype model of the electromagnetic field generator.
5. Future work will consist of using these data for design of a control system for the electromagnetic field generator for system of cleaning of clots in small cavities by utilizing FF and travelling magnetic wave and the ultrasound catheter.

References

1. Ferrofluids [interactive]. Internet source: http://www.mrsec.wisc.edu/Edetc/background/ferrofluid/index.html.
2. **Gould P.** Nano magnetism shows in-vivo potential. Nanotoday. ISSN:1748 0132 © Elsevier Ltd 2006.
3. **Lin J., Shapiro B., Probst R.** Particle steering by active control of magnetic fields, and magnetic particle agglomeration avoidance. ISR Technical Report 2008. P.22.
4. Measuring magnetic field strengths using ferrofluids [interactive]. Internet source: http://www.nsec.ohio-state.edu/teacher_workshop/Measuring_Magnetic_Fields.pdf
5. **Willard M. A., Kurihara L. K., Carpenter E. E., Calvin S. and Harris V. G.** Chemically prepared magnetic nanoparticles. IoM Communications Ltd and ASM International. 2004.
6. Ferrofluids [interactive]. Internet source: http://mrsec.wisc.edu/Edetc/modules/HighSchool/ferrofluid/Ferrofluids-Background.pdf.
7. Ferrofluid [interactive]. Internet source: http://en.wikipedia.org/wiki/Ferrofluid#cite_note-two-0.
8. Ferrofluid in magnetic field [interactive]. Internet source: http://commons.wikimedia.org/wiki/File:Ferrofluid_in_magnetic_field.jpg
9. Magnetic lines of various magnets [interactive]. Internet source: http://my.execpc.com/~rhoadley/gallery/imageset.html.

K. Šileika, I. Skiedraitė

Ferinio skysčio judėjimo daugiapoliame elektromagnetiniame lauke tyrimas

Reziumė

Eksperimentiniai duomenys, gauti matuojant magnetinio lauko indukciją pasirinktuose taškuose, esančiuose tarp dviejų solenoidų, padėjo nustatyti reikiamus solenoidų poliškumus. Stebėta, kaip tarp dviejų aktyvių solenoidų, sukūrus tinkamų krypčių magnetinius laukus, teka ferinis skystis. Be to, pasiūlytas įrenginio, skirto kraujagyslių vidinėms sienelėms valyti, prototipas. Jame naudojamas ferinis skystis ir ultragarsinis kateteris.

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