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Technology and applications

Magnetic fluid and nanoparticle applications to nanotechnology

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Abstract

Magnetic field based micro/nanoelectromechanical systems (MEMS/NEMS) devices are proposed that use 10 nm diameter magnetic particles, with and without a carrier fluid, for a new class of nanoduct flows, nanomotors, nanogenerators, nanopumps, nanoactuators, and other similar nanoscale devices. A few examples of macroscopic ferrohydrodynamic instabilities that result in patterns, lines, and structures are shown that can be scaled down to sub-micron dimensions.

Background to magnetic fluid technology

Present electric field based microelectromechanical system (MEMS) technology of solid capacitive structures can be extended to include magnetic field interactions with ferrofluids and submicron size magnetic particles for micro/nanoelectromechanical system (MEMS/NEMS) devices.

Ferrofluids, which are synthesized as a stable colloidal suspension of permanently magnetized particles such as magnetite of 10 nm diameter, are an excellent choice for such NEMS magnetic field technology. Brownian motion keeps the 10 nm size particles from settling under gravity, and a surfactant is placed around each particle to provide short range steric repulsion between particles to prevent particle agglomeration in the presence of non-uniform magnetic fields (Rosensweig, 1985).

Conventional ferrofluid applications use DC magnetic fields from permanent magnets for use as a liquid O-ring in rotary and exclusion seals, as dampers in stepper motors and shock absorbers, and for heat transfer in loudspeakers (Berkovsky & Bashtovoy, 1996). Almost every computer disk drive uses a magnetic fluid rotary seal for contaminant exclusion and the semiconductor industry uses silicon crystal growing furnaces that employ ferrofluid rotary shaft seals.

Ferrofluids also have very interesting lines, patterns, and structures that can develop from ferrohydrodynamic instabilities as illustrated in Figures 1 and 2 for the ferrofluid peaking behavior resulting from a magnetic field perpendicular to the free surface of a ferrofluid layer; in Figure 3 for the gear-like structure resulting from the radial perpendicular field instability when a small magnet is placed behind a ferrofluid drop confined between closely spaced glass plates; and in Figures 4 and 5 for the labyrinth instability that results when a magnetic field is applied tangent to the thin dimension of a ferrofluid layer confined between closely spaced glass plates. All pictures use a ferrofluid with saturation magnetization of 400 G. In Figures 3–5 the ferrofluid is surrounded by a 50% propanol/50% deionized water mixture in order to prevent the ferrofluid from wetting the glass plates.

These applications concern macroscopic systems but because the ferrofluid particles have a particle diameter of order 10 nm, there are also many potential new MEMS/NEMS applications using ferrofluid particles, with and without carrier fluid, for nanoduct flows, nanomotors, nanogenerators, nanopumps,

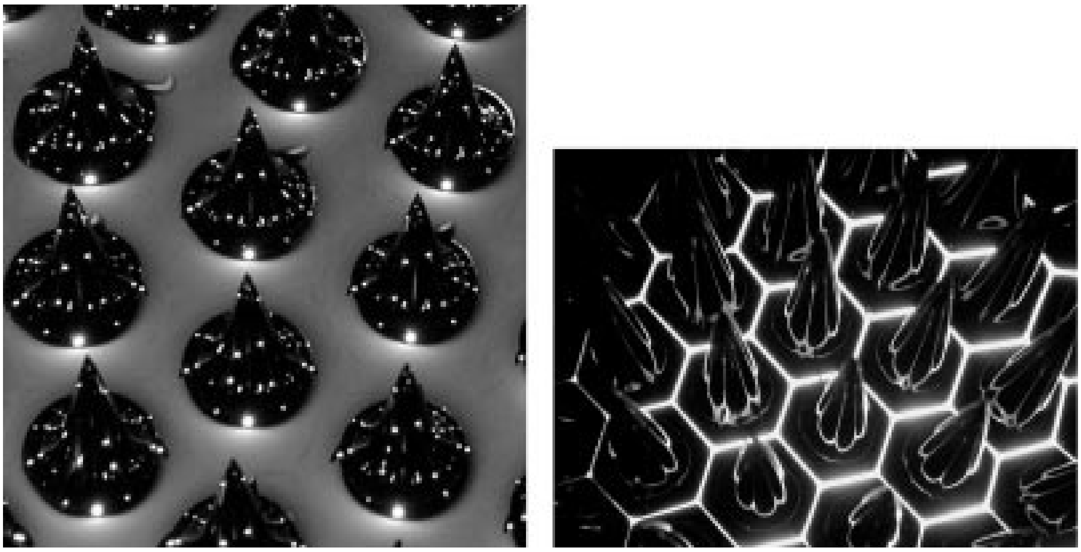

Figure 1. Hexagonal peaking patterns of about 1 cm spacing result when a perpendicular magnetic field is applied to a layer of magnetic fluid with saturation magnetization of 400 G. The peaks initiate when the magnetic surface force exceeds the stabilizing effects of the fluid weight and surface tension. The left picture shows the 'chocolate-drop' like shape with an applied perpendicular field of about 200 G while the right picture shows the sharp peaks with a hexagonal base pattern with a magnetic field of about 330 G.

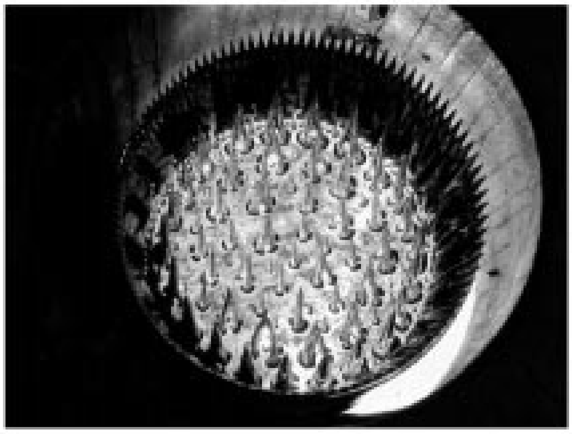

Figure 2. Another view of the perpendicular field instability including a crown of peaks on the glass container wall edge when a 400 G magnetic field is applied. The containing vessel has 15 cm diameter.

nanoactuators, and other similar nanoscale devices (Gazeau et al., 1997). The feature size and line widths of ferrohydrodynamic phenomena like that shown in Figures 1–5 can be scaled down to sub-micron dimensions with micro-volumes of ferrofluid and perhaps using non-magnetic contacting fluids that greatly lower the interfacial tension at the ferrofluid interface.

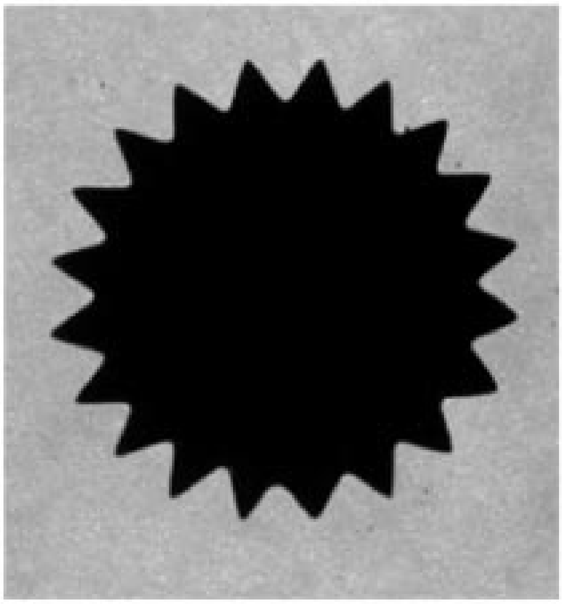

Figure 3. Gear-like structure that results when a small 5 mm diameter permanent magnet with strength of about 1200 G is placed behind a small ferrofluid droplet confined between glass plates with 1 mm gap.

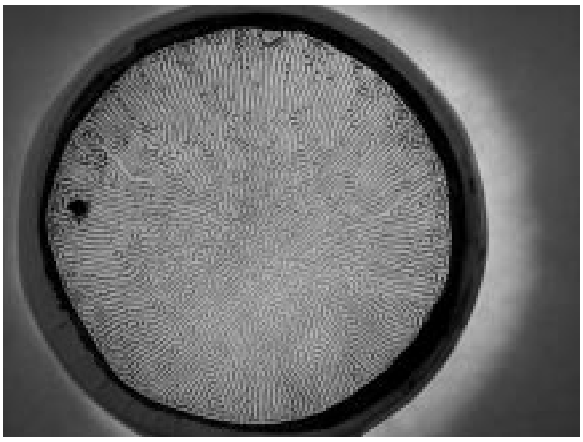

Figure 4. Labyrinth instability that results when a 1 mm thick layer of ferrofluid between 4 inch diameter glass plates is stressed by a magnetic field of about 250 G tangent to the thin dimension of the ferrofluid layer.

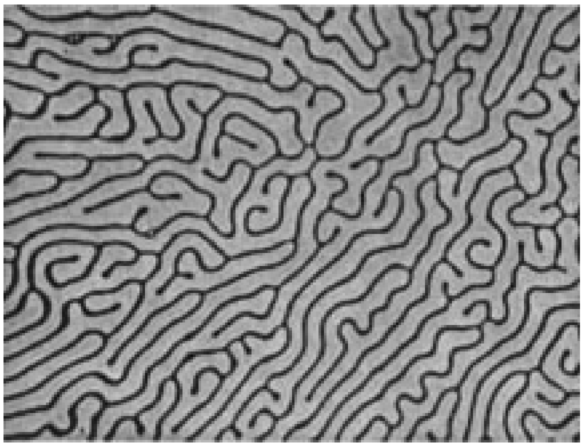

Figure 5. Closer view of the labyrinth instability, like that shown in Figure 4, with picture width about 3 cm.

Solid structures can be made from ferrofluid that is solid at room temperature but becomes liquid at slightly elevated temperature, such as by using a paraffin based ferrofluid. If the ferrofluid is heated and then cooled in the presence of a magnetic field, solid magnetic nanostructures can be fabricated such as the gear-like structure in Figure 3. Solid spiked structures with shapes like those in Figures 1 and 2 may be useful for forming high electric fields at the tips that can be used in charge injection devices.

To show the advantages of magnetic field based MEMS and NEMS devices over the usual electric field based MEMS devices we can compare representative electric and magnetic energy densities. An electric field device is generally limited by the maximum allowed electric field without electrical breakdown, typically $E \approx 10^8$ V/m for small scale devices that take advantage of the Paschen curve at small gaps to raise the electrical breakdown strength of air; for example a variable capacitance micromotor may use 150 V across a 1.5 μm gap (Mehregany et al., 1992). Magnetic field devices have no limitation analogous to electrical breakdown and the maximum magnetic flux density is of the order of saturation magnetization of single domain magnetic particles, about $B \approx 2.1$ T for single domain iron particles. The resulting electric and magnetic energy densities are then:

$$W_e = 0.5\,\varepsilon_0 E^2 \approx 4.43 \times 10^4\ \mathrm{J/m^3};$$
$$W_m = 0.5\,B^2/\mu_0 \approx 1.75 \times 10^6\ \mathrm{J/m^3}.$$

This possible increase in energy density and resulting forces for magnetic devices has the added advantage of increased reliability as there are no catastrophic failure mechanisms analogous to electrical breakdown.

Ferrofluid behavior in AC magnetic fields

The motion of ferrofluid in a traveling wave magnetic field has been paradoxical as many investigators find a critical magnetic field strength below which the fluid moves opposite to the direction of the traveling wave (backward pumping) while above the critical magnetic field strength the ferrofluid moves in the same direction (forward pumping) (Calugaru et al., 1976; Zahn & Wainman, 1993; Zahn & Greer, 1995; Zahn & Pioch, 1998, 1999). The value of critical magnetic field depends on the frequency, concentration of the suspended magnetic particles, and the fluid dynamic viscosity. Under AC magnetic fields, fluid viscosity acting on the magnetic particles suspended in the ferrofluid causes the magnetization **M** to lag behind an oscillating or traveling **H**. With **M** not collinear with **H**, there is a body torque density $\mathbf{T} = \mu_0 \mathbf{M} \times \mathbf{H}$ acting on the ferrofluid even in a uniform magnetic field. This torque causes the ferrofluid nanoparticles to rotate which results in a nanoscale flow field around the particles that can result in a decrease of effective fluid viscosity, termed 'negative viscosity' (Shliomis & Morozov, 1994; Bacri et al., 1995; Rosensweig, 1996; Zeuner et al., 1998, 1999). A theoretical model predicts the effective viscosity as a function of magnetic field amplitude, frequency, and direction and preliminary experiments have verified the analysis. According to this theory, there is a range of magnetic field parameters that can drive the effective viscosity to zero or negative values. A true 'zero viscosity' fluid has been measured using a controlled stress parallel plate rheometer with one plate rotating for the dielectric analog system of 80 μ diameter polymethylmethacrylate (PMMA) particles in transformer oil that rotate due to Coulombic forces on particle surface charge in a DC electric field (Lobry & Lemaire, 1999). Under the 'zero viscosity' limit the rheometer plate rotates without any applied torque, with the plate rotation caused by the electric field induced particle rotations.

Micro/nanoscale flow and pump devices with representative channel width of 100–1000 nm can be fabricated where ferrofluid is pumped using alternating and traveling magnetic fields. A preliminary design plans to use the imposed magnetic fields to greatly lower the effective fluid viscosity so that a significant flow rate can be obtained with modest pressure drops. The ferrofluid will be predominantly pumped by the magnetic field induced nanoparticle rotations.

Proposed mechanical and electrical micro power generation using rotating magnetic particles

Isolating individual magnetic particles

Single ferrofluid particles with or without a carrier liquid can be isolated using a quadrapole magnetic field array, a magnetic dual analogy to a microfabricated cell sorter that uses dielectrophoretic polarization forces in a planar quadrapole electrode array to confine and sort biological cells (Voldman et al., 2000; Green & Morgan, 1997). Dielectrophoresis based single-particle traps can hold single bioparticles against destabilizing fluid flows using simple electrode configurations that create quadrapole and higher order multipole electric fields. Simple current carrying coil arrangements can similarly produce magnetic particle traps.

Another concept has particles positioned in arrays of periodic depressions surrounded by two deposited sets of conductors which are 90° out of phase in space and carrying sinusoidally varying currents which are 90° out of phase in time in order to create a rotating magnetic field. A preliminary concept to filling the depressions with ferromagnetic particles is to use a high vapor pressure carrier fluid, which can easily evaporate leaving the particles behind to roll into the depressions. To reduce rolling friction perhaps the particles can be coated. Vibration may further coax the particles into the depressions. To have the magnetic particles rotating in synchronism the substrate may need to have a planar permanent magnet layer so that all the particles have their magnetic axes initially aligned in the same direction.

It is important to realize the probable difficulties in manipulating, detecting, moving, and rotating 10 nm diameter particles, due to van der Waals forces which cause nanoparticles to tend to stick to the substrate.

Motor and generator operation

By placing individual 10 nm diameter magnetic particles in such traps, a rotating magnetic field causes the particles to spin forming a rotary nanomotor that can be operated as a synchronous machine. Solid nanogears like that shown in Figure 3 can provide electromechanical coupling between rotating nanoparticles in order to get significant macroscopic mechanical output power contributed from all the particles.

These devices may also be operated in reverse for nanogenerator operation where particles are put into motion by imposed ferrofluid or air driven flows generating electric power in surrounding nanocoil windings by changing the magnetic flux with time through the nanocoils. Figure 6 schematically illustrates a concept of how waste heat can be used to induce a ferrofluid flow that controllably rotates ferrofluid nanoparticles near a coil to cause a time rate of change of magnetic flux through the coil so that current flows through the coil.

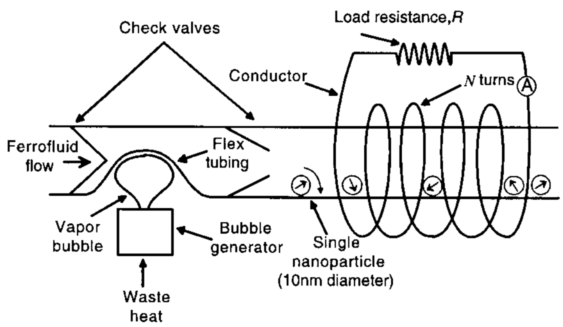

Figure 6. Schematic diagram of a proposed power supply method that takes waste heat to cause a time varying flow that controllably rotates ferrofluid nanoparticles so that there is a time varying magnetic flux through a coil that induces a current through a load.

It may be necessary to place a permanent DC magnet at the inlet of the flow so that all magnetic dipole moments of the nanoparticles are initially aligned so that the resulting ferrofluid rotation and translation of magnetic particles are synchronized and matched to the coil winding geometry so that all magnetic particle induced magnetomotive forces add rather than have random contributions that statistically add to zero. The vapor bubble pump has been considered by NASA as a means of converting heat energy to mechanical and electrical energy. One proposal uses pumped ferrofluid to generate electric power in the space station using concepts along the lines shown in Figure 6.

Representative present technology can fabricate copper coil windings that are about 5 μm thick, 100 μm wide, with radius of curvature of order 200 μm. A circular loop of copper with these dimensions would have approximate resistance of 0.25 Ω. Possible superconducting windings could greatly lower this resistance so that for a given electromotive force much larger currents could flow. A 10 nm ferrofluid magnetite particle magnetized to 0.6 T would have magnetic flux of about 5×10^{-17} Wb. If this particle rotated next to our representative coil at an angular speed of 1000 revolutions per second so that all the magnetic flux of the particle linked the coil, the induced peak voltage would be about 3×10^{-13} V. The short circuit peak current would then be this voltage divided by the coil resistance, or about 1 picoampere for a copper coil winding. The maximum power that could be delivered by this single particle generator would be about 3×10^{-25} W. If confined to a single plane, there could be as many as 10^{16} such single nanoparticle generators per square meter. If connected in series, the open circuit peak voltage could be as high as 3000 V per square meter of generator surface, while if connected in parallel the short circuit peak load current could be as high as 10 000 A per square meter of generator surface or in more practical units for nanoscale devices, about 0.01 $\mu A/(\mu m)^2$ of generator surface area. The delivered time average power would then be of order 3×10^{-9} W/m^2.

Of course practical packing constraints, small wafer sizes, smaller particle rotation rates, particle sticking, particle confinement, and other non-idealities and problems of controlling motions of nanoparticles would lower these idealized large values, but these ‘back-of-the-envelope’ preliminary calculations indicate the practical possibility of generating useful levels of micropower for selected applications such as for nanosciencecraft planned by NASA.

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References

Bacri J.-C., R. Perzynski, M.I. Shliomis & G.I. Burde, 1995. ‘Negative Viscosity’ effect in a magnetic fluid. Phys. Rev. Lett. 75(11), 2128–2131.

Berkovsky B. & V. Bashtovoy, 1996. *Magnetic Fluids and Applications Handbook*, Begell Home, Inc.

Calugaru G.H., C. Cotae, R. Badescu, V. Badescu & E. Luca, 1976. A new aspect of the movement of ferrofluids in a rotating magnetic field. Rev. Roum. Phys. 21, 439–440.

Gazeau F., C. Baravian, J.-C. Bacri, R. Perzynski & M.I. Shliomis, 1997. Energy conversion in ferrofluids: Magnetic nanoparticles as motors and generators. Phys. Rev. E 56(1), 614–618.

Green N.G. & H. Morgan, 1997. Dielectrophoretic separation of nano-particles. J. Phys. D: Appl. Phys. 30, L41–L44.

Lobry L. & E. Lemaire, 1999. Viscosity decrease induced by a DC electric field in a suspension. J. Electrostat. 47, 61–69.

Mehregany M., S.D. Senturia, J.H. Lang & P. Nagarkar, 1992. Micromotor fabrication. IEEE Transac. Elect. Dev. 39(9), 2060–2069.

Rosensweig R.E., 1996. ‘Negative viscosity’ in a magnetic fluid. Science 271, 614–615.

Rosensweig R.E., 1985. *Ferrohydrodynamics*, Cambridge University Press, Cambridge.

Shliomis M.I. & K.I. Morozov, 1994. Negative viscosity of ferrofluid under alternating magnetic field. Phys. Fluids 6(8) 2855–2861.

Voldman J., R.A. Braff, M. Toner, M.L. Gray & M.A. Schmidt, 2001. Holding forces of single-particle dielectrophoretic traps. Biophys Journal 80, 531–541.

Zahn M. & D.R. Greer, 1995. Ferrohydrodynamic pumping in spatially uniform sinusoidally time-varying magnetic fields. J. Magnet. Mag. Mat. 149, 165–173.

Zahn M. & L.L. Pioch, 1999. Ferrofluid flows in AC and traveling wave magnetic fields with effective positive, zero or negative dynamic viscosity. J. Magnet. Mag. Mat. 201, 144–148.

Zahn M. & L.L. Pioch, 1998. Magnetizable fluid behaviour with effective positive, zero, or negative dynamic viscosity. Ind. J. Eng. Mat. Sci. 5, 400–410.

Zahn M. & P.N. Wainman, 1993. Effects of fluid convection and particle spin on ferrohydrodynamic pumping in traveling wave magnetic fields. J. Magnet. Mag. Mat. 122, 323–328.

Zeuner A., R. Richter & I. Rehberg, 1998. Negative viscosity in a dispersion of magnetite. Abstracts of the 8th International Conference on Magnetic Fluids, Timisoara, Romania, pp. 72–73.

Zeuner A., R. Richter & I. Rehberg, 1999. On the consistency of the standard model for magnetoviscosity in an alternating magnetic field. J. Magnet. Mag. Mat. 201, 191–194.