Ferrofluids

Presented to

The Faculty of the Department of Physics

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Arts

By

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June, 2011

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Figure 1: An ordinary wood screw coated in Ferro fluid with a permanent neodymium magnet underneath. Photo by Richard Kwok.

1. Introduction

Ferrofluids are truly fascinating. Technologically savvy artists have been able to capture the human imagination with little but a judicious application of a magnetic field. The substance seems to defy gravity, flowing and shaping itself seemingly like magic (see Figure 1). The true magic, however, is the vast range of properties that this intrinsically simple substance can exhibit. It can vary its viscosity given the strength of the magnetic field. It can draw heat away from an over worked mechanical component. It can even split a beam of light in two. It's hard to imagine what kind of strange and incredibly complex process would result in such miraculous material. Clearly, such a material must be made up of some highly advanced ingredients, the likes of which the world can scarcely fathom. As it turns out, the situation is quite the opposite. Ferro fluids are little more than iron particles suspended in oil.

A true ferrofluid is classified as a colloidal suspension of small magnetic particles in a carrier liquid. The most common magnetic material in use is magnetite (Fe_3O_4). Although the use of hematite (Fe_2O_3) is not unheard of, magnetite is far more widely used. In order to achieve an even greater level of stability, a surfactant can also be used to act as a separating agent, which will be discussed later.

The carrier fluid can be a number of substances. Simple water will do, but for practical applications, the vast majority of manufacturers employ the use of a hydrocarbon such as kerosene (hydrocarbons having a strong affinity for attaching itself to the lipid based surfactants used). The particulars of the ingredients in any particular brand's mixture seem to be considered a trade secret. The result is a solution that responds to a magnetic field in very curious ways.

Ferrofluids are considered paramagnetic as opposed to ferromagnetic, and are sometimes referred to as being "super paramagnetic." Their extreme magnetic susceptibility is due to the relatively miniscule size of the particles. When a simple bar magnet is placed under a container of ferrofluid, the substance will immediately align itself to the lines of equipotential emanating from the poles as seen in Figures 1, 2 and 3.

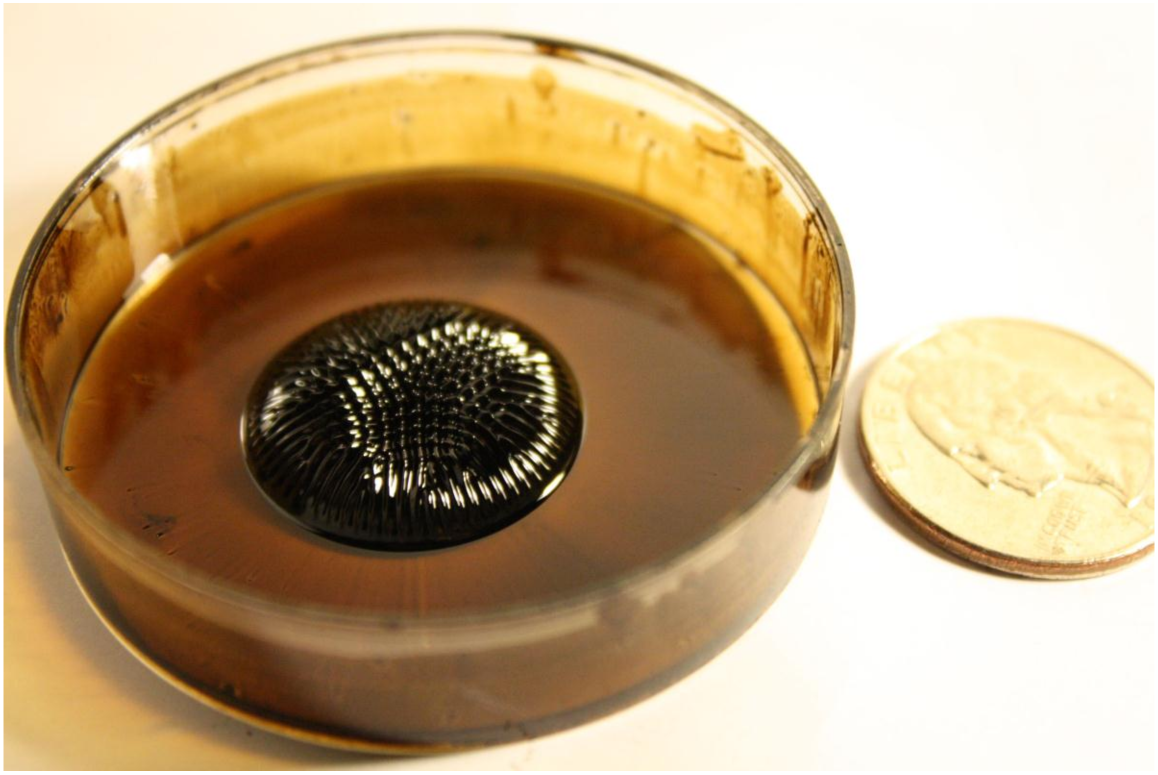

Figure 2: Ferro fluid under a strong magnetic field. In this case a rare earth neodymium magnet has been placed directly below the container. One can notice the more numerous yet smaller protrusions. A US quarter is used for scale. Photo by Richard Kwok.

The stronger the magnetic field, the smaller and more numerous the "spikes" are, compare Figures 2 and 3. Under a weaker magnetic field the effect is more pronounced, making fewer but larger spikes. If allowed to contact the magnet directly, the fluid will coat the surface, concentrating mostly about the poles. This creates an almost frictionless object, which is able to glide across a smooth surface similar in effect to a hydroplane.

Figure 3: Ferro fluid under a slightly weaker magnetic field. The same permanent magnet with the same amount of fluid but the magnet is now separated from the container by half a centimeter. Notice that the protrusions are lager and less numerous. Photo by Richard Kwok.

These phenomenal properties (as well as others) have inspired people to imagine a number of real world applications. Ferrofluids are currently being used in high quality speakers and microphones, automotive suspension components, computer hard drives and more. The current development of ferrofluids has undergone much advancement, but there are still obstacles to overcome. We have only begun to scratch the surface of possibilities of this incredibly versatile technology.

2. How Does it Work?

As previously stated, ferrofluids are comprised of tiny particles of iron oxide suspended in solution. This brings to mind the immediate question of how small these particles need to be. Simply adding conventional powdered iron (the size of which is on the order of μm) to liquid produces a fairly unstable result. If allowed enough time, the particles will sink to the bottom or otherwise agglomerate. Furthermore, the iron will come out of suspension and solidify in the presence of a strong enough magnetic field, thus negating the practicality. Such substances are known as magneto rheological fluids. This suggests three criterion for stability of a true ferrofluid: the particles must not settle under gravitational forces, the particles must not clump together under the influence of a magnetic field, and the particles must not agglomerate naturally.

In order for the particles to overcome settling or concentration in a magnetic field, they must be small enough for their Brownian motion to overcome the opposing forces. The energies involved are as follows:

Thermal - k_BT
Gravitational - $\Delta\rho Vgh$
Magnetic - $\mu_0 M_p HV$

Where k_B = Boltzmann constant, T = absolute temperature, $\Delta\rho$ = difference in density between the particles and the liquid, V = volume of particles, g = acceleration of gravity, h = height of liquid, μ_0 = permeability of free space, M_p = magnetization of particles, H = magnetic field.

Stability with regards to gravitational forces is expressed by the following equation:

$$k_BT/(\Delta\rho Vgh) \geq 1$$

Where $k_B T$ represents the thermal energy and $\Delta\rho Vgh$ represents the gravitational potential energy.

For the ease of example we'll assume spherical particles with radius r and diameter d = 2r. Substituting the volume of a sphere for V we get:

$$3\, k_B T/(4\Delta\rho\pi r^3 gh) \geq 1$$

Inserting some practical real world values:

$\Delta\rho$= 4,300 kg^{-3} (magnetite)
h = 0.05 m (size of a small container)
T = 300K (room temperature)

This leaves us with a particle, which can at the most be approximately 15 nm in diameter.

Similarly, to obtain a value for d capable of staying in suspension under the influence of a magnetic field:

$$k_B T/(\mu_0 M_p H V) \geq 1$$

In this instance the thermal energy is now divided by $\mu_0 M_p HV$, which represents the magnetic potential.

With values:

M_p = 4.46 x 10^5 A m^{-1} (magnetite)
H = 8 x 10^4 A m^{-1} (approximately 20 times the strength of a normal refrigerator magnet)

We come to a diameter of no more than 6 nm.

This leads us to the third and most challenging obstacle to overcome: agglomeration. The suspended particles themselves act as small dipoles.

> In the same way, at very short distances the van der Waals force between particles is attractive. The thermal energy needed to oppose the agglomeration of dipolar origin has the same order of magnitude as that which opposes sedimentation. However, agglomeration of Van der Waals [sic] origin is irreversible since the energy required to separate two particles, once agglomerated, is very large. Consequently it is necessary to find a way of preventing the particles from getting to close to each other.[i]

There are two methods used to achieve this distancing effect. One of which is to electronically charge the magnetic particles. Ferrofluids generated by this method are known as "ionic ferrofluids." This process is generally considered to be the easiest method of production. One simply collects sediment from a solution of iron salts, typically ferrous chloride ($FeCl_2$) or ferric chloride ($FeCl_3$). Electrostatic repulsion keeps the magnetic dipoles from getting close enough to each other and agglomerating. This is the preferred method of synthesizing homemade ferrofluids due to its simplicity and relative availability of materials.

The second, more complicated method, involves milling magnetite in the presence of a surfactant. This process can be quite time intensive. Not surprisingly, these ferrofluids are referred to as "surfacted ferrofluids." A surfactant is a detergent-like substance. One end of the molecule attaches to the surface of the particle, whereas the other end is more attracted to the liquid. This achieves a single layered polymer coating that prevents the dipole particles from attaining the critical "clumping" proximity. This process has the added benefit of making the magnetic material more lipid soluble, thus increasing the variety of carrier fluids that can be used. This is the preferred method of manufacturing commercial ferrofluid, as mass production is the only feasible way to make the effort worthwhile.

3. Properties

As can be expected, the introduction of a magnetic field has consequences on the apparent viscosity of a ferrofluid. The base viscosity of the fluid is largely dependant on the carrier fluid used. It is furthermore naturally increased slightly by the introduction of the magnetic material in suspension. The term "apparent viscosity" is used here because the density of the fluid (which is the usual determining factor in viscosity) is not the primary actor. While it is true that the application of a magnetic field will, in fact, compress the fluid slightly, the direct force of the magnetic field overshadows this effect.

> When a magnetic field is applied and the ferrofluid is subjected to a shearing force, the particles tend to remain with the field. The velocity gradients around the particles in the fluid, and hence the viscosity, are then increased. When the *vorticity* of the fluid is parallel to the applied field, the particles can rotate freely, and the field has no effect on viscosity. By contrast, if the field and the vorticity are perpendicular to each other, the increase in viscosity due to the field is maximal.[ii]

This is to say that a magnetic field can grant a ferrofluid a type of "directional viscosity." If a force would act on the fluid that does not disrupt the alignment of the magnetic particles to the field, the force will not be opposed. If, however, the force would misalign the particles it would be opposed, simulating an increase in viscosity. This is a cause for concern for would-be developers. The shape of the alignment (spikes) is uniform and symmetric, but does not particularly resemble any usable shape.

The magnetic particles suspended in ferrofluids have been shown to display a property known as optical birefringence. Most substances are considered to be "isotropic." This is to say that incident light is refracted equally regardless of direction. This is most commonly seen in common transparent material, such as glass or water. Substances that are considered "anisotropic" behave somewhat differently. The incident light is split into two rays. As light enters its optical axis it is refracted much like an isotropic substance, changing it's velocity uniformly and thus altering its angle of refraction uniformly. When light enters a non-equivalent axis, it is refracted into two rays, each polarized so that they travel at different velocities and that their vibration directions are oriented at right angles to one another.[iii]

The ability of ferrofluids to display this birefringence is due to its ability to be fluid and in structured alignment simultaneously. Its unique nature as a group of aligned particles suspended in solution allows it to mimic the crystalline structure of an anisotropic substance such as calcite. Moreover, ferrofluids are able to display a "linear birefringence." In a zero field the magnetic material is uniformly distributed and arbitrarily oriented. In this instance the birefringence is also zero. As one applies a magnetic field in varying degrees, the particles align themselves proportionate to the strength of the field. This gives us the ability to adjust the birefringence effect. See Figure 4.

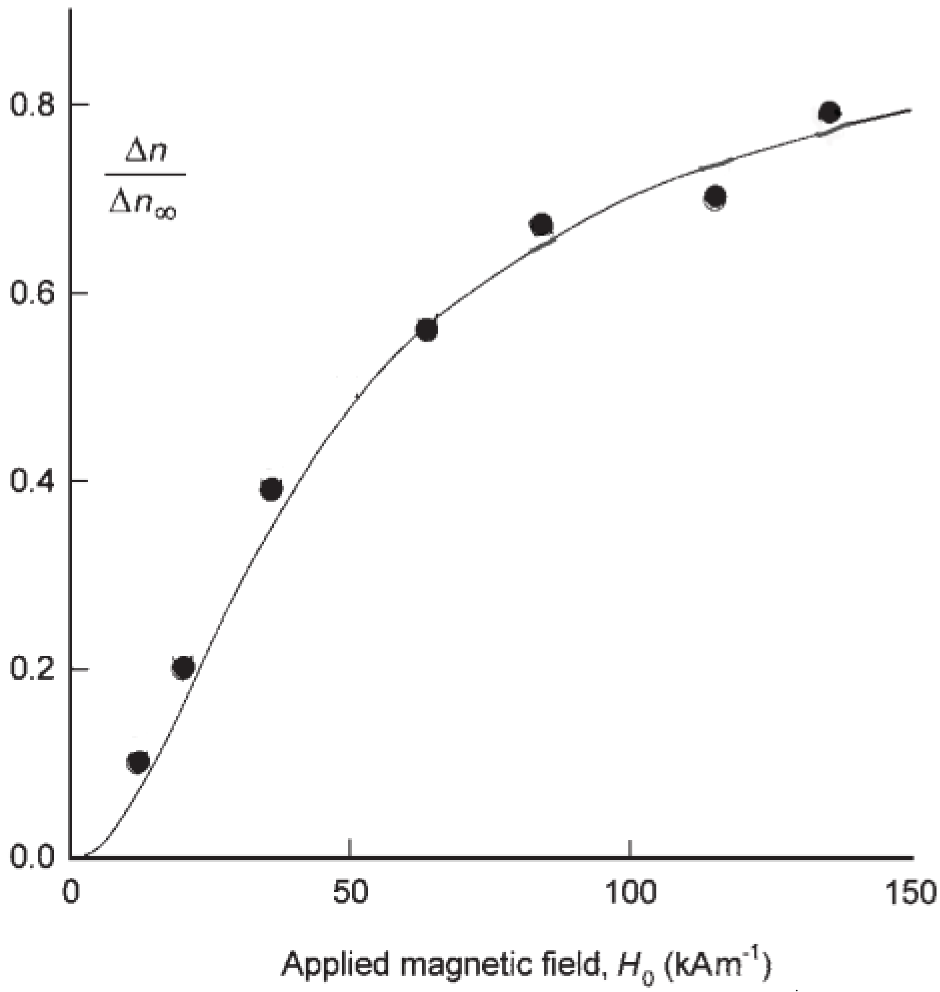

Figure 4: Theoretical and experimental birefringence results[iv]
We can clearly see that the magnetic field (H) has a direct relation to the ratio of the index of refraction between the divergent rays of light. Graph from Concise encyclopedia of magnetic and superconducting materials.

4. Applications

Ferrofluids have a number of applications that researchers have been successful in implementing. These applications spring from both the malleability of the substance, and its ability to respond to electric stimuli. Seeing as magnetic fields can interact with a Ferrofluid at a distance, we can directly influence fluid in a seemingly closed system. Furthermore, the variety of carrier fluids that can be used offers even more versatility.

Since ferrofluid is both liquid and magnetic, it can be introduced as a seal and held in place by a permanent magnet. A perfect example of this is creating a dust seal on a spindle. If the spindle is a permanent magnet and the carrier liquid used is oil based, the fluid will be held in place almost indefinitely, thus creating a semi-permanent lubricating seal. This method has the advantage over conventional rubber seals in that there is no material to wear down. This reduces maintenance (replacing worn seals) and eliminates dust contamination of the system (causing further wear on other components).

Ferrofluids also have a natural heat sinking ability. Curie's Law states that the ratio of the magnetization of a paramagnetic substance to the magnetizing force is in inverse proportion to the absolute temperature. This is illustrated in the formula:

$$M = C \times (\mathbf{B}/T)$$

Where M is the magnetization, **B** is magnetic field, T is the absolute temperature, and C is a material specific curie constant.[v] In a ferrofluid, the magnetic particles are suspended in liquid and are therefore relatively free to respond to the forces applied to them. In the earlier example of a spindle seal, the particles close to the permanent magnet are getting the most heat from friction. This heat then reduces the magnetization of the particles in suspension. The cooler, more magnetic particles are then drawn towards the magnet, pushing the warmer ones towards the outside where they can then release their heat to the universe.

Ferrofluids have recently been employed in the field of automotive suspension. In 2002 The Delphi corporation in conjunction with General Motors introduced a system called MagneRide. Typically, the dampening of oscillations in a vehicle's suspension system is attained by forcing highly viscous oil through relatively small orifices. With the use of Ferro fluids, we can directly influence the viscosity of the dampening fluid with an electromagnetic field.

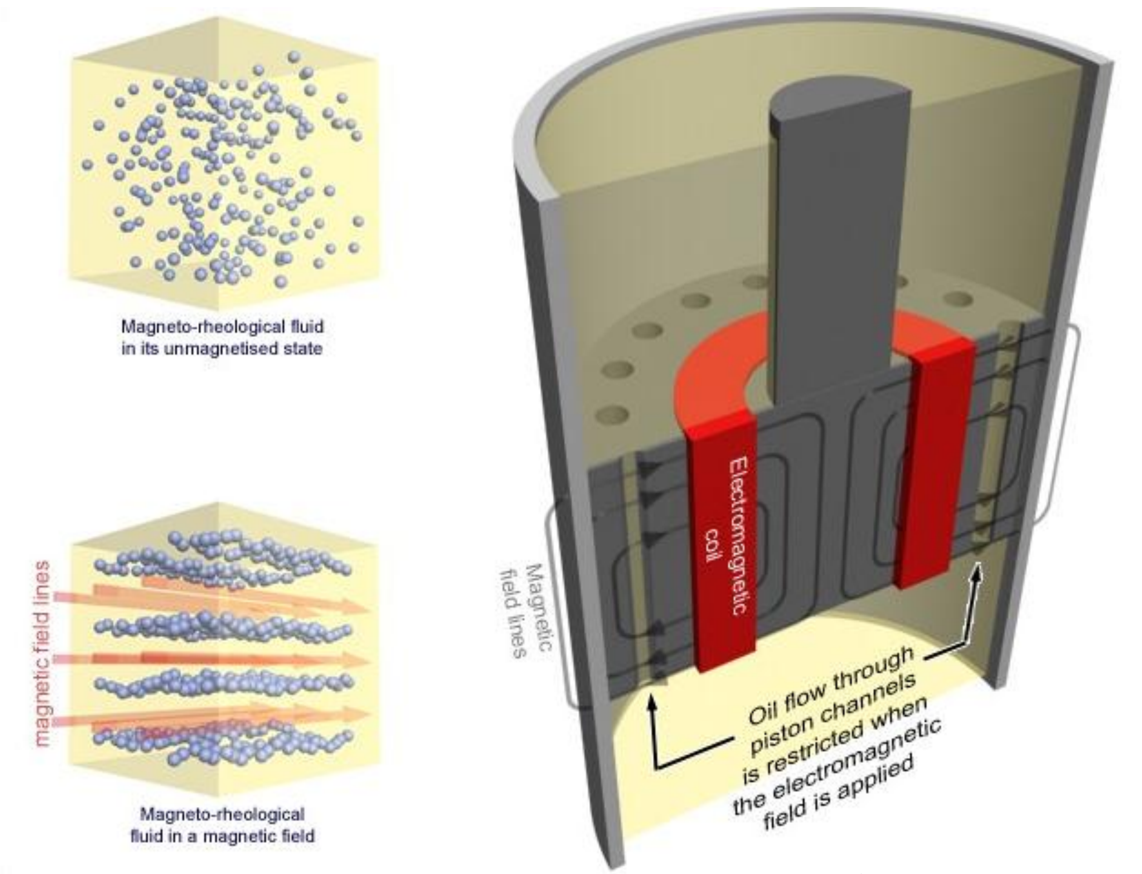

Figure 5: MagneRide Suspension Cutaway[vi]
As the magnetic particles align to the magnetic field lines, the force required to push the oil through the orifices is increased. Image from Audi MagneRide.

This, combined with the aid of an onboard computer, gives us precise control of driving dynamics and cabin comfort. "The… system is a continuously adaptive system - i.e. it's a closed feedback loop that can react to changes both in the road surface and the gear-changes (front-to-back weight shift) within milliseconds."[vii] This ability to instantaneously react to ever changing road conditions increases not only driving performance but safety as well. Computer control allows the tires to track the road more precisely, thus maximizing their contact with the road. More contact gives rise to more frictional force applied to the driving surface, therefore increasing the amount of control that the driver can exert on the vehicle.

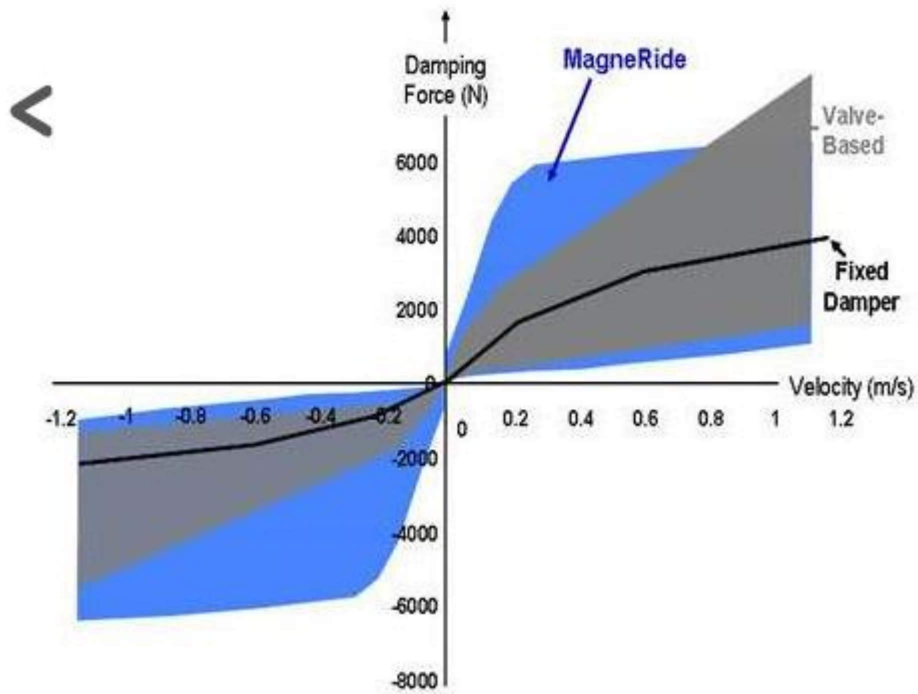

Figure 6: MagneRide compared to conventional dampeners.[viii]
The dampening force per unit of velocity (as it applies to the compression and rebound of the suspension) is drastically increased. Image from BMI Group.

5. Conclusion

It is without saying that ferrofluids have a very unique nature. Their physical make up is surprisingly simple. At a basic level they're iron shavings added to an appropriate liquid. Their physical properties however could not be more varied and astounding. It can penetrate small orifices, lubricate, change the direction and polarization of a beam of light, or even just mesmerize a curious onlooker. These two properties grant an amazing array of applications that researchers have only begun to imagine. A long life, self-lubricating, and self-cooling seal has countless applications in medical technology. Mechanical implants can be imagined that don't require maintenance (thus avoiding the problem of removing a device that's been implanted). Oil, which responds to electromagnetic radiation, has a multitude of conceivable applications as well. Imagine hydraulic piston that can be actuated by radio waves, or an automobile crankshaft that can concentrate different amounts of oil to specific bearings as it needs. Obviously there are obstacles to be overcome. Some sort of non-toxic Ferrofluid would need to be formulated to be put into a human body. Nonetheless, because of its simplicity in concept, Ferro fluid technology is highly adaptable. Several types of fluid with a wide variety of properties (boiling point, viscosity, specific gravity, etc.) can be synthesized. There is very little doubt that Ferro fluids will play a significant part in future technological development. They will serve not only to improve current technology, but also to drastically expand the horizon of what we think that machines are capable of.

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i Magnetism: materials and applications.

ii Ibid.

iii http://micro.magnet.fsu.edu/optics/lightandcolor/birefringence.html

iv Concise encyclopedia of magnetic and superconducting materials.

v http://www.britannica.com/EBchecked/topic/146922/Curies-law

vi http://www.carbibles.com/suspension_bible_pg3.html - ixzz1AsXAvSJb

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viii http://www.bwigroup.com/static/suspension_magneride/

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