Imaging complex magnetic field patterns using ferrofluid as a visualization tool and the disruption of the normal field instability

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1. Introduction

The goal was to try and capture an image demonstrating the effects of a complex magnetic field on the ferrofluid, and the resulting disruption of the normal field instability caused using water-based acrylic paint. This report demonstrates the basic science, the process involved in imaging the phenomena, and the post processing techniques used to bring out the vibrancy in the final image. Dr. Hertzberg provided the ferrofluid. Team 5 developed the idea (collaborators and self).

2. Flow Phenomena

A ferrofluid is a suspension containing magnetic particles (with mean diameters around 10 nm) in a carrier fluid (Holm and Weis, 2005). The particles only have a single magnetic domain and hence act as tiny permanent magnets in the carrier fluid (Holm and Weis, 2005). The fluid as a whole is *superparamagnetic*, which is a kind of magnetism exhibited in extremely tiny ferromagnetic substances. This basically means that if the magnetic field causing the spikes is removed, the spikes do not retain their structure that way, as the particles are no longer magnetized (Neuberger et al., 2005). When the ferrofluid is subjected to a (usually vertically oriented) magnetic field, there is visible formation of spikes and valleys. These are favorable to the system, from the point of view of magnetic energy (equation given below), where B is the magnetic field and the integral is evaluated over the region of existence of the magnetic field. This regular pattern is called the *Normal Field Instability* (or *Rosensweig effect*). The layer of ferrofluid exposed to a uniform magnetic field, exhibits this instability above a critical value of the magnetic field, and if the strength of the magnetic field were increased, there would be a smooth transition from a hexagonal array to a square array (Abou et al., 1999). Unfortunately we did not have the capacity to conduct the experiment with varying magnetic field strengths.

$$E = \frac{1}{2}\int H.B\,dV$$

A structure of magnets was created (as shown in Figure 2 (left)) that had the center stacked with a flipped pole. The corner stacks were repulsive with each other. When the normal field instabilities of induced by separate magnets (flipped orientation – attractive) overlap, the nearest spikes combine to form a bridge like structure (as shown in Figure 1 (top)). This is observed near the center as seen in the final image (Figure 4). When repulsive forces are induced with magnets (same orientation – repulsive), as the separate structures move closer, the spikes seem to deflect away from the center (as shown in Figure 1 (bottom)). This is also clearly demonstrated in the final image (Figure 4).

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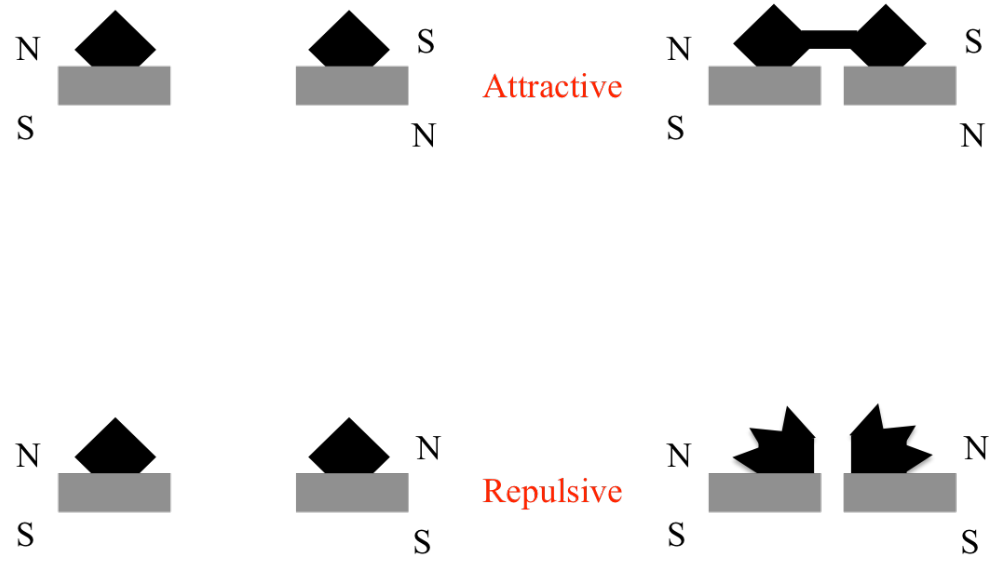

Figure 1: Effects on ferrofluid instability structure based on orientation of polarity of magnets

The resulting structure was static and not flowing, hence dimensionless numbers describing flow (*Re*, *Gr* etc.,) are not calculated in this report.

3. Flow Visualization Technique

Water–based acrylic paint was used as a tracer for this image. The base fluid used was a ferrofluid (provided by Dr. Hertzberg). The container used was clear glass, to observe the flow. The lighting had to be placed behind the background, so as to allow diffuse/ indirect light, due to the high specular reflectivity of the ferrofluid. Common circular magnets, easily available at any hardware store were used and the dimensions were as follows: Large (1" OD), Small (3/4" OD). The center magnet stack had the poles flipped from the rest of the side stacks, as shown in Figure 2 (left). The glass container was rested on this stack after the ferrofluid was poured inside, and the paint (with equal parts water) was added. The resulting structure and paint cells were mobile for a few seconds and stabilized. The entire structure (ferrofluid) was about 3" in height and width when it formed.

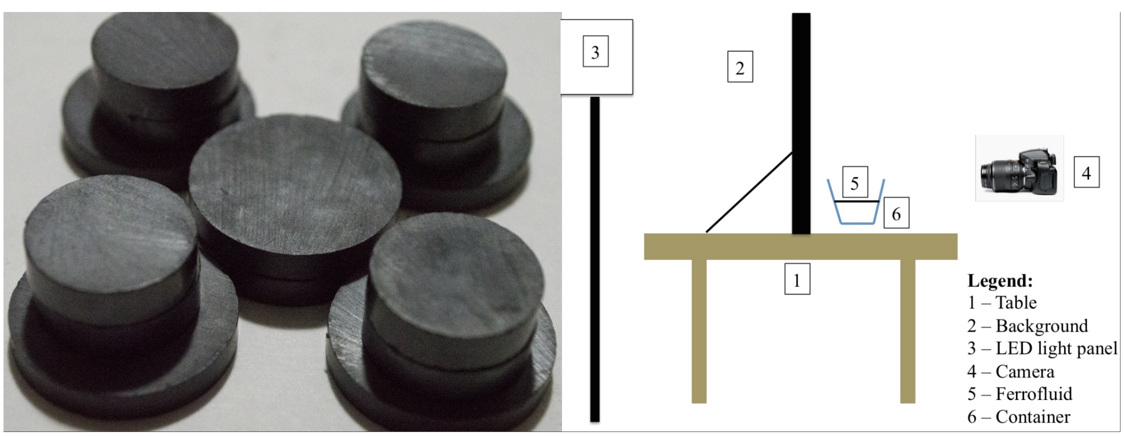

Figure 2: Magnetic arrangement (left) and Setup used for imaging (right)

4. Photography Technique

The Camera used was a Nikon D3200 with an 18–55 lens (DSLR digital camera). As shown in Figure 2, the camera was hand–held, and kept orthogonal to the lighting source. The required parameters are listed and calculated as follows:

1. *Lens Specs* – Focal length: 46 mm, F number (f/): 5.6
2. *Exposure specifications* – Shutter Speed: 1/13 sec, ISO: 12800, Aperture size = 8.2mm(1)
3. *Camera and Image* – Nikon 3200 DSLR (digital), Original (w x h) = 6016 x 4000 pixels, Final (w x h) = 3960 × 3350 pixels
4. *Distance of object (to lens)*: 10.7 in(2)
5. *Field of View*: 5.4 in x 3.6 in(3).
6. *Final cut processing (Photoshop)*: The self-explanatory Figure 3 summarizes the adjustments made in Photoshop of the original image, and Figure 4 shows the image before and after processing.

   Reasons for choosing the mentioned settings: The ferrofluid is very dark (black) but also very reflective. As mentioned in *Section 3*, the specular reflection caused due to direct lighting would interfere with the image and block certain portions of the cells formed by the paint on the fluid. Hence, a lower ambient lighting situation called for the highest ISO possible, which is 12800 for the camera used. Since a tripod was not used, the shutter speed was fairly quick, and the aperture was wide open. The focus was set at 1/3rd height from the bottom, to get a clearer view of the spikes while not obscuring the paint cells in the center.

Calculations:

[1]Aperture size: $D = F/f\# = 46 \text{ mm} / 5.6 = \underline{8.2 \text{ mm}}$

[2]Distance to lens: a non-conventional formula was used:

$$Ob = \frac{F(\text{mm}) \times \text{Real Height (mm)} \times \text{Image Height (Pixels)}}{\text{Object Height (Pixels)} \times \text{Sensor Height (mm)}} = \frac{46 \times 76.2 \times 4000}{3350 \times 15.4} = 271.77 \text{ mm} = \underline{10.7 \text{ in}}$$

Angle of view (degrees):

$$= \left(\arctan\left[\text{Sensor Width (mm)} / (2 \times F(\text{mm}))\right]\right) = 14.15^{\circ}$$

$$= \left(\arctan\left[\text{Sensor Height (mm)} / (2 \times F(\text{mm}))\right]\right) = 9.5^{\circ}$$

[3]Hence Field of View =

$$2 \times (\tan(\text{Angle of View}) \times Ob) = 2 \times (\tan(14.15) \times 271.77) = 137 \text{ mm} = \underline{5.4 \text{ in}}$$

$$2 \times (\tan(\text{Angle of View}) \times Ob) = 2 \times (\tan(14.15) \times 271.77) = 91 \text{ mm} = \underline{3.6 \text{ in}}$$

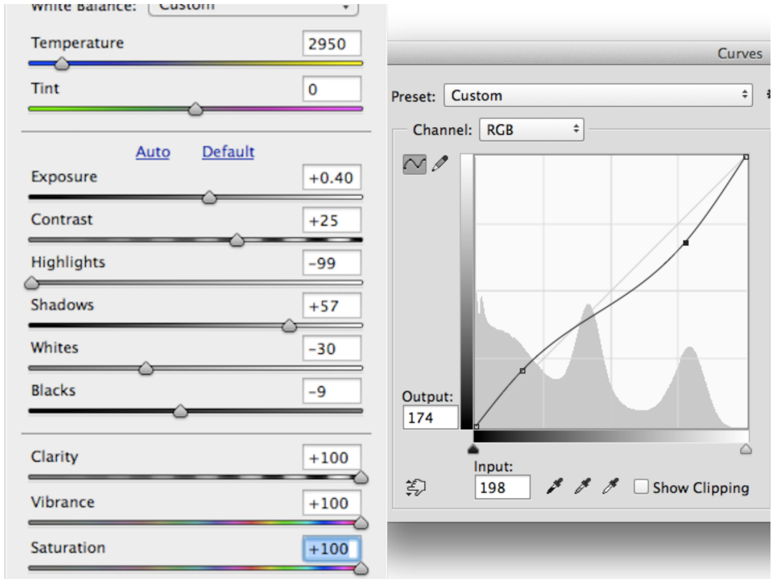

Figure 3: (a) Menu on the left was used first and then (b) curves were edited as shown on the right

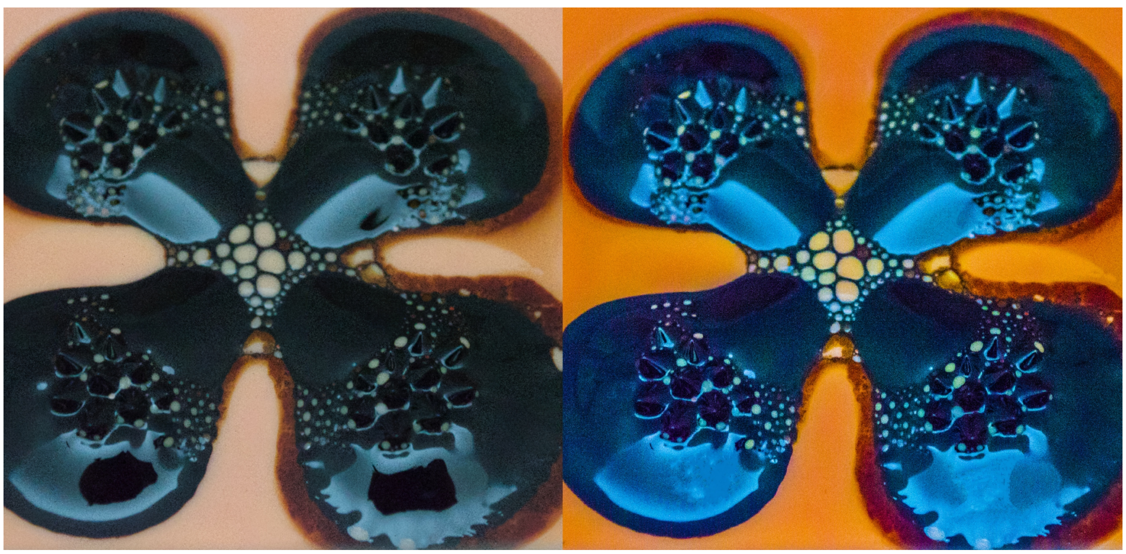

Figure 4: Unedited (left) and Edited (right) versions of Image

5. Image Characteristics

As seen in Figure 4, we can clearly see the effect of the complex magnetic field. The 4 bridges connecting the center of the structure to the “leafs” of the 4–leaf clover shaped ferrofluid are created due to the attractive side of the magnet turned up in the magnet. The rest of the magnets cause ample repulsion that pushed the leaves to appear symmetrical, and the spikes leaning away slightly. The paint is suspended in the center and in the narrow band caused as a result of the magnetic field. Due to the hydrophobic nature of the ferrofluid, the water-based acrylic paint would only form near the spikes, and not on the bridges or the slopes. Post processing made the image sharper and the edges better defined when compared to the original. From an artistic point of view, the goal was to simulate an “Alien 4–leaf clover with dew” and the color modifications give a sense of that.

6. References:

Holm C., Weis J., J. (2005), "The structure of ferrofluids: A status report", *Current Opinion in Colloid & Interface Science* (2005), 10: p133 – 140.

Neuberger T., Schöpf B., Hofmann H., Hofmann M., Rechenberg B., v. (2005), "Superparamagnetic nanoparticles for biomedical applications: Possibilities and limitations of a new drug delivery system", *Journal of Magnetism and Magnetic Materials* (2005), 293: p483 – 496.

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