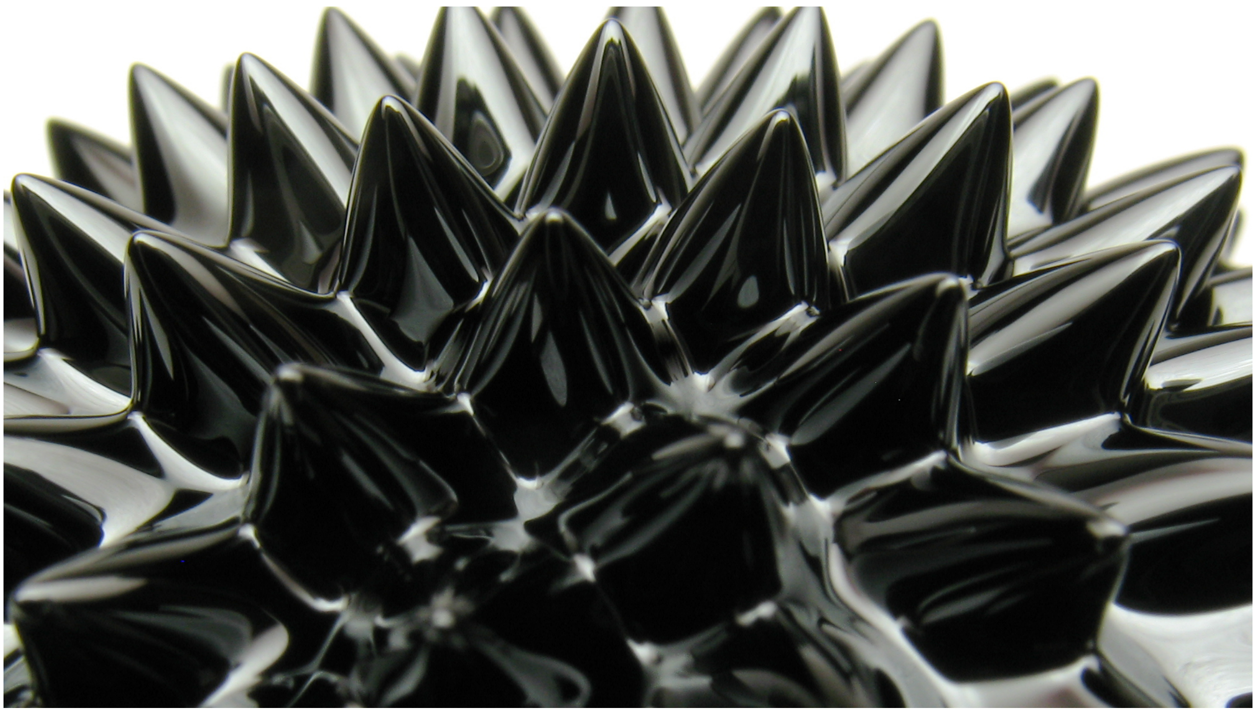
# MCEN 5141: Flow Visualization

## Team Third



Andrew A. Van Der Volgen

# 1 Introduction

This project was intended to provide an opportunity for application of the techniques covered thus far in the MCEN5141 course curriculum. Its aim was to create a fluid flow indicative of an arbitrary fluid mechanic phenomena and image it effectively. Although several flows were considered, ferrofluid was ultimately settled on as a subject for imaging with the intent of highlighting its unusual characteristic behavior while subjected to a magnetic field.

# 2 Major Materials

## 2.1 Ferrofluid

Traditionally, ferrofluid is created through the combination of nanoscale magnetite ($Fe_30_4$) particles which are covered in surfactant, and an organic solvent. Due to the small scale of the magnetite particles, they remain suspended in solution by Brownian motion and the surfactant prevents them from clumping together [1]. This results in a fluid which has traditional Newtonian properties, but is also uniformly magnetic. As a result, ferrofluid responds to the presence of magnetic fields and can be manipulated by them.

Ferrofluid is readily available commercially from many different scientific and industrial supply companies. It is sold in both small and bulk quantities. For this project only a small amount was necessary and so two fluid ounces of FerroTec brand fluid was purchased online from an industrial supply distributor.

## 2.2 Magnets and Miscellaneous

Although several magnets were experimented with, the image on the title page of this document was created with a single 17.5mm diameter Neodymium disc magnet. Magnets of this type are widely available online and locally at most hardware stores.

Once ferrofluid comes in contact with a magnet it is difficult to remove or recover the fluid. For this reason it was desirable to keep the fluid out of contact with any magnets while attempting to image it. This was accomplished by putting the subject fluid into a petri dish and bringing magnets into its proximity from under the dish.

There were times throughout the project when it was necessary to add or subtract small amounts of fluid from the bulk in the petri dish. For convenience, this done with a syringe.

# 3 Setup and Image Capture

To produce the final image, 30 milliliters of ferrofluid were put into a petri dish with a single disc magnet directly below the fluid under the dish. A Canon Powershot A640® camera on a JOBY Gorrilapod Original® tripod was set up in front of the dish with the lens 1cm away from the subject fluid. A plain piece of A5 paper was placed behind the dish to serve as a uniform background for the photo. Finally, the fluid was illuminated by a 5000K color temperature, 2000 lumen, LED work light which was positioned directly above, and pointed straight down at, the dish.

With this setup, images of the ferrofluid were taken at 3648 $\times$ 2736 resolution, 1/15s shutter speed, f/8 aperture, ISO 80, and with a focal length of 7mm. The resultant raw image chosen to represent this project is presented in Figure 1.

Figure 1: Raw Image

This photo was then post-processed in Adobe Photoshop. The image was cropped down to 2007 $\times$ 1126 resolution to remove reflections of the camera and create a macro perspective of the peaks and valleys induced by the normal-field instability (see section 4). Photoshop's *Curves* tool was also used to adjust contrast, although the adjustment was extremely subtle given the already high contrast range of the raw photo. The resultant image depicts a 16 $\times$ 9mm field of view and is shown on the title page of this document.

# 4 Fluid Mechanics

## 4.1 Normal-Field Instability

The characteristic development of peaks and valleys in the ferrofluid surface is known as the *Rosensweig* or *normal-field instability*. Although not the only instability that ferrofluid can exhibit, it is the most well known and that which was captured in this project's image.

The instability forms when fluid is subjected to a uniform vertically-oriented magnetic field. The introduction of magnetic force increases the surface energy of the fluid which then modulates in response to attain a new minimum energy state. This state takes the form of the normal-field instability and is an equilibrium of surface, gravitational, and magnetic energies [1].

From Figure 1 it is plain to see that the instability only forms under certain conditions, as some of the areas cropped out for the final image do not experience it. This condition can be expressed by a critical magnetization value, $M_c$, in its dimensionless form [2]:

$$\frac{\mu_0 M_c^2}{\sqrt{g\Delta\rho_m\sigma}} = 2\left(1 + \frac{1}{r_p}\right)$$

where $\mu_0$ is the permeability of a vacuum, $g$ is the gravitational constant, $\Delta\rho_m$ is the difference in mass densities of fluids across the interface (typically ferrofluid-air), $\sigma$ is the interfacial tension, and $r_p$ is the dimensionless permeability ratio:

$$r_p = \left(\frac{\mu_c\mu_t}{\mu_0^2}\right)^{1/2}$$

Areas where magnetization exceeds this critical value exhibit the characteristic instability, while elsewhere the fluid does not. Once criteria for development of the instability have been reached, its repetitive peak-and-valley shape can be described by the spacing between peaks, $\lambda$, which at onset of the instability is given by [2]:

$$\lambda = 2\pi\left(\frac{\sigma}{g\Delta\rho_m}\right)^{1/2}$$

## 4.2 Varying Viscosity

Cursory experimentation with ferrofluid immediately makes clear that the fluid's apparent viscosity increases when subjected to static magnetic fields. To quantify this, it is first necessary to describe the native viscosity of a *colloid*, a class of fluids containing stably suspended particles, of which ferrofluid is a member. Einstein's expression for the viscosity of a colloid applies and is expressed as:

$$\eta_0 = \eta_c\left(1 + \frac{5}{2}\widetilde{\phi}\right) \qquad \text{where} \qquad \begin{array}{l} \eta_0 \text{ is the colloid viscosity} \\ \eta_c \text{ is the carrier fluid viscosity} \\ \widetilde{\phi} \text{ is the volume fraction of suspended particles} \end{array}$$

However, this expression has been shown empirically to be inaccurate for $\widetilde{\phi} > 0.1$. Ferrofluids often exceed this volume fraction of suspended particles, and as such, Rosensweig developed a colloid viscosity expression that is accurate for $\widetilde{\phi}$ up to roughly 0.3 [2]. It takes the form:

$$\eta_0 = \eta_c\left(1 - \frac{5}{2}\widetilde{\phi} + \left(\frac{5}{2}\widetilde{\phi}_c - 1\right)\left(\frac{\widetilde{\phi}}{\widetilde{\phi}_c}\right)^2\right)^{-1}$$

where $\widetilde{\phi}_c$ is a critical volume fraction where the solid suspended particles dominate the behavior of the substance and the colloid becomes rigid.

Now consider the case where a ferrofluid is subjected to an externally applied static magnetic field. Deriving a viscosity expression for the fluid under these conditions is beyond the scope of this document, however, it has been shown by Schliomis that the normalized change in viscosity is bounded by [4]:

$$\frac{\Delta\eta}{\eta_0} \in \left[0, \frac{3}{2}\widetilde{\phi}\right]$$

That is to say that the viscosity of a ferrofluid always increases when subjected to a static magnetic field, but can never exceed a normalized maximum value of $\frac{3}{2}\widetilde{\phi}$. It is important to note that this holds only for static magnetic fields. Application of time-varying fields has the potential to decrease ferrofluid viscosity under certain circumstances [3].

# 5 Conclusion

Creating interesting ferrofluid formations which exhibit the normal-field instability is relatively trivial, however the physics governing their formation is complex, and imaging the resultant formations can be difficult. Care must be taken to avoid distracting reflections of the surrounding environment in the fluid, and proper lighting is critical in generating the contrast necessary for effective visualization. Despite these complications, the image produced for this project is visually striking and effectively displays high-resolution detail of the normal-field instability exhibited by ferrofluid.

## References


[1] David Andelman and Ronald E. Rosensweig. *The Phenomenology of Modulated Phases: From Magnetic Solids and Fluids to Organic Films and Polymers*. World Scientific, 2009.

[2] R.E. Rosensweig. *Ferrohydrodynamics*. Cambridge University Press, 1985.

[3] Mark I. Shliomis and Konstantin I. Morozov. Negative Viscosity of Ferrofluid Under Alternating Magnetic Field. *Physics of Fluids*, 6(8):2855–2861, 1994.

[4] M.I. Shliomis. Effective Viscosity of Magnetic Suspensions. *Zh. Eksp. Teor. Fiz*, 61(6):2411–2418, 1972.