Ferrofluid Flow and Torque Measurements in Rotating Magnetic Fields

by

Adam D. Rosenthal

Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of Master of Engineering in Electrical Engineering and Computer Science at the

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Abstract

The purpose of this research is to provide data from ferrofluid flow and torque measurements in uniform and nonuniform rotating magnetic fields that can be compared to theoretical analyses in order to fully understand observed paradoxical ferrofluid behavior. In the presence of rotating magnetic fields, ferrofluid particles will rotate to try to align their magnetic moment with the field but because of the fluid viscosity, magnetization $M$ will lag behind the rotating $H$ field, thereby resulting in a body torque on the ferrofluid. The viscous torque from this fluid flow is measured using a Couette viscometer as a function of magnetic field amplitude, frequency, and direction of rotation. The first three sets of experiments measure this torque on the outer wall of a Lexan spindle that is attached to a viscometer, functioning as a torque meter. The spindle is immersed in a beaker of ferrofluid centered inside a 2-pole or 4-pole motor stator winding, creating uniform or nonuniform rotating magnetic fields, respectively. The spindle rotates at a constant speed up to 100 rpm or is stationary in these measurements. Anomalous behaviors such as zero and negative magnetoviscosity are demonstrated and discussed. The next set of experiments measure the magnetic torque on the inner wall of a hollow spindle attached to the torque meter and filled completely with ferrofluid so that there is no free surface. The spindle is centered inside the motor stator windings and exposed to clockwise (CW) or counterclockwise (CCW) rotating magnetic fields. The last set of experiments measures the surface spin rate of a small floating plastic ball placed on the ferrofluid surface at a fixed location as a function of magnetic field parameters and radial position on the surface. When the rotating magnetic fields induce ferrofluid flows, the ball spins in the opposite direction to magnetic field rotation and this spin rate is determined using frame-by-frame video analysis.

Thesis Supervisor: Markus Zahn
Title: Professor
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7 Spin Rate Experiments

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The spin rate seemed to be the same for all radii, implying rigid body motion.

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CCW spin rate increased approximately linearly with magnetic field amplitude.
The spin rate seemed to be the same for all radii, implying rigid body motion.

A2 Experimental Parts

A2.1 The solid Lexan (polycarbonate) spindle used for the torque measurements
in Chapters 3-5. Only the bottom half of the spindle was immersed in ferrofluid
(61mm depth). The threaded inset on the top of the spindle was attached to the
Brookfield viscometer by screwing it on to the viscometer fixture.

A2.2 The solid Lexan (polycarbonate) spindle used for the torque measurements
in Chapters 3-5. Only the bottom half of the spindle was immersed in ferrofluid
(61mm depth). The threaded inset on the top of the spindle was attached to the
Brookfield viscometer by screwing it on to the viscometer fixture.

A2.3 The partially hollow Lexan spindle filled with ferrofluid used for the
torque measurements in Chapter 6. The wall spindle thickness is 3mm, so the
ferrofluid diameter is 19.6 mm. The top was attached to the Brookfield
viscometer.

A2.4 The partially hollow Lexan spindle filled with ferrofluid used for the
torque measurements in Chapter 6. The wall spindle thickness is 3mm, so the
ferrofluid diameter is 19.6 mm. The top was attached to the Brookfield
viscometer.

A2.5 The large Lexan spindle referred to in section 5.1 that was incompatible
with the Brookfield viscometer. The upper section of diameter D1 was solid
while the lower section of diameter D2 was hollow, in order to reduce the
weight of the spindle and to allow the option of filling with ferrofluid for
additional experiments. Despite attempts to lower spindle weight and to balance
for no wobble, this spindle would still not operate properly with the Brookfield
viscometer.
A2.6 The large Lexan spindle referred to in section 5.1 that was incompatible with the Brookfield viscometer. The upper section of diameter D1 was solid while the lower section of diameter D2 was hollow, in order to reduce the weight of the spindle and to allow the option of filling with ferrofluid for additional experiments. Despite attempts to lower spindle weight and to balance for no wobble, this spindle would still not operate properly with the Brookfield viscometer.

A2.7 The glass ferrofluid container used for the torque experiments in Chapters 3-5. The container wall thickness is 2.40mm. The spindle was centrally aligned inside the vessel with the bottom of the spindle cylinder 2.6 mm above the bottom of the container. The whole assembly was centered inside the motor stator windings.

A2.8 The glass ferrofluid container used for the torque experiments in Chapters 3-5. The container wall thickness is 2.40mm. The spindle was centrally aligned inside the vessel with the bottom of the spindle cylinder 2.6 mm above the bottom of the container. The whole assembly was centered inside the motor stator windings.

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A2.10 The ferrofluid container, a 300mL glass beaker, used for the spin rate experiments in Chapter 7. The container wall thickness is 3.2 mm. The container fit snugly in the 2-pole motor stator winding.

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A2.12 The 2-pole motor stator winding used in the experiments in Chapters 3-7 to create uniform rotating magnetic fields. The casing thickness is 2.3mm.

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A2.14 The 4-pole motor stator winding used in the experiments in Chapters 3 to create nonuniform rotating magnetic fields. The casing thickness is 2.8mm.

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Chapter 1
Introduction

1.1 Background

Ferrofluids are magnetic fluids that are synthesized as a stable colloidal suspension of permanently magnetized particles, such as magnetite (Fe₃O₄), typically of order 10nm diameter. Brownian motion prevents these small particles from settling under gravity. A surfactant is placed around each particle to provide short-range steric repulsion between particles (Figure 1.1), preventing particle agglomeration in the presence of non-uniform magnetic fields [1]. These particles are immersed in a carrier fluid, such as the water based or oil based fluids used in this thesis.

1.1.1 Ferrohydrodynamic Instabilities

Much of the previous ferrofluid research investigates the behavior of ferrofluids in DC magnetic fields, such as the patterns and structures that result from ferrohydrodynamic instabilities. Figures 1.2 and 1.3 illustrate the ferrofluid peaking behavior resulting from a magnetic field perpendicular to the free surface of a ferrofluid layer. Figure 1.4 shows a 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. Figures 1.5 and 1.6 demonstrate 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 in Figures 1.2-1.6 use an Isopar-M ferrofluid with a saturation magnetization of 400 Gauss [2].
Figure 1.1: The three components of a ferrofluid: spherical permanent magnetic core, surfactant layer, and carrier fluid [1].

Figure 1.2: 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 Gauss. 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 Gauss while the right picture shows the sharp peaks with a hexagonal base pattern with a magnetic field of about 330 Gauss [2].
Figure 1.3: Another view of the perpendicular field instability including a crown of peaks on the glass container wall edge when a 400 Gauss magnetic field is applied. The containing vessel has 15 cm diameter [2].

Figure 1.4: Gear-like structure that results when a small 5 mm diameter permanent magnet with strength of about 1200 Gauss is placed behind a small ferrofluid droplet confined between glass plates with 1 mm gap [2].
Figure 1.5: 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 Gauss tangent to the thin dimension of the ferrofluid layer [2].

Figure 1.6: Closer view of the labyrinth instability, like that shown in Figure 4, with picture width about 3 cm [2].
1.1.2 Ferrofluid Applications

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 enhanced heat transfer in loudspeakers [3].

There are numerous biomedical applications of ferrofluids that are presently being researched. Magnetic drug targeting [4-9] uses ferrofluids by coating the magnetic particles with a surfactant that favorably binds with a selected drug. Using an applied magnetic field, the injected “magnetic drug” can be guided to the desired area in the body. These methodologies can be utilized to treat pathologies such as atherosclerosis, offering advantages over biodegradable polymers such as repeated treatments with the drug and drug monitoring using MRI. Ferrofluids can be used for hyperthermia [10-16] by exposure of ferrofluid to high frequency alternating magnetic fields, causing the magnetite particles to vibrate and converting the energy to heat. Precision heating can be obtained by varying the magnetic field strength and frequency. The hyperthermia can be used to heat and destroy tissues (e.g. tumor therapy). Other applications include removing toxic substances from the body, using methods like those in magnetic drug targeting; magnetic cell sorting [17]; ferrofluid driven actuators and micropumps to assist pumping mechanisms in the body [18]; delivering nutrients for tissue engineering; imaging the activity of bioelectrical systems such as the heart and brain; and many others. Toxicity studies are currently being performed to evaluate the biocompatibility of magnetic particles in the body [19-22].

Ferrofluids also have possible applications in nanotechnology. Magnetic field based micro/nanoelectromechanical systems (MEMS/NEMS) could produce a new class of devices such as nanomotors, nanogenerators, nanopumps, nanoactuators, and other similar nanoscale devices. Solid structures can be formed from ferrofluids that are solid at room temperature but melt at higher temperatures, such as using a wax ferrofluid. Gear-like structures, like that in Figure 1.4, can be formed if the solid ferrofluid is heated to melt and then cooled in the presence of a magnetic field. Solid spiked structures like that in Figures 1.2 and 1.3 can be used to form high electric fields at the tips for charge...
injection devices [2]. Other potential applications include magnetic fluid-based sensors [23] and magnetic fluid transducers [24].

Recent work has made progress in designing magnetic micropumps using ferrofluids [25]. The device uses ferrofluids to drive the flow and as a valve, controlled by a permanent magnet on a small motor. These devices serve as a novel technology, but they are limited in size, speed, and cost. Therefore it would be desirable to create a magnetic micropump using ferrofluids, with no moving parts and controlled solely by externally applied magnetic fields, no longer limiting the technology by restrictions on the motor parameters.

1.2 Literature Review of Ferrofluid Flows in Rotating Magnetic Fields

Analyses and measurements [26-31] have shown anomalous behavior of ferrofluids in alternating and rotating magnetic fields, whereby the effective fluid viscosity can be increased or decreased and the ferrofluid can be pumped but the flow direction can reverse as a function of magnetic field amplitude, frequency, and direction. This anomalous behavior can be explained using the governing fluid mechanical linear and angular momentum conservation equations including nonsymmetric Maxwell and viscous stress tensors. Analytical solutions for simple limiting cases show that the effective dynamic viscosity, or magnetoviscosity, can be made positive, zero, or negative. Although a zero electroviscosity has been experimentally measured for a dielectric suspension in rotating electric fields [32], there has been no previous work that has experimentally measured a zero or negative magnetoviscosity. The work presented in this thesis is the first to do so. An excellent review of the ferrofluid literature as well as theoretical modeling appears in the thesis of Carlos Rinaldi [33].

Past work has analyzed ferrofluid pumping in a planar duct driven by spatially uniform and non-uniform traveling wave magnetic fields [34-37]. Other analyses have been done in a cylindrical geometry [38-60]. Typically, these experiments place ferrofluid in a
cylindrical container subjected to a time-varying magnetic field. Some researchers [38, 54, 55] have used magnetic field sources that are uniform and rotating in the absence of ferrofluid so that there is no body force density \( f = \mu_0 (\mathbf{M} \cdot \nabla) \mathbf{H} \) but there is a torque density \( T = \mu_0 (\mathbf{M} \times \mathbf{H}) \). In other cases [39], the field source is non-uniform and rotating in the absence of ferrofluid so that there is a nonzero magnetic body force.

Regardless of the magnetic field type, the basic observations show that in a stationary container, the ferrofluid is observed to rotate rigid-body-like in a direction, which depends on the applied magnetic field amplitude and frequency. This rigid-body-like motion is observed in the inner core of ferrofluid and extends right up to the stationary cylindrical vessel wall. To make these observations, tracer particles are placed on the rotating free surface. Since ferrofluids are opaque, it is difficult to observe bulk flow profiles beneath the surface.

The general conclusion of the literature is that the ferrofluid and the magnetic field rotate in opposite directions. However, some authors [39, 41, 53] report observations where the ferrofluid switches between co-rotation and counter-rotation with respect to the applied magnetic field amplitude and frequency. Explicitly, Brown and Horsnell (1969) observe co-rotation of field and ferrofluid flow for low magnetic fields and counter-rotation for high magnetic fields, whereas Kagan et al. (1973) and Calugaru et al. (1976) observe counter-rotation for low magnetic fields and co-rotation for high magnetic fields. Preliminary observations made in this thesis support the results obtained from Brown and Horsnell for a water based ferrofluid in a three phase two-pole motor stator winding creating a uniform magnetic field. A more detailed experimental study of these observations is needed in future work.

Observations of counter-rotation of field and fluid led Brown and Horsnell (1969) to investigate the direction to which a cylindrical container would rotate if it could freely do so. This represents an indirect measurement of the magnetic torque applied to the ferrofluid. One would expect the counter-rotating fluid to drag the cylindrical container along with it, but, as stated in their title “The Wrong Way Round”, experiments show the
container co-rotating with the field whereas the fluid counter-rotates. Such observations have since been corroborated by Kagan et al. (1973) and Rosensweig et al. (1990).

Various authors [1, 38, 40, 42-52, 55, 60] have attempted theoretical analyses aimed at understanding these experimental observations. The classical analysis [40] assumes the magnetic field throughout the ferrofluid region is uniform, neglecting the demagnetization factor. The resulting body-couple is uniform whereas the magnetic body-force is exactly zero. The flow field in the ferrofluid is determined analytically using the phenomenological structured continuum theory [61-63], which includes the effects of antisymmetric stresses, body-couples, and body stresses representing the short-range surface-transport of internal angular momentum.

1.3 Scope of Thesis

The purpose of this research is to provide data from ferrofluid flow and torque measurements in uniform and nonuniform rotating magnetic fields that can be compared to theoretical analyses, such as the theory developed by Carlos Rinaldi [33], in order to fully understand observed paradoxical ferrofluid behavior. In the presence of rotating magnetic fields, ferrofluid particles will rotate to try to align their magnetic moment with the field but because of the viscous fluid, magnetization M will lag behind the rotating H field, thereby exacting a body torque on the ferrofluid. The torque from this fluid flow is measured and described in this thesis as a function of magnetic field amplitude, frequency, and direction of rotation. The first three sets of experiments in Chapters 3-5 measure this torque on the outer wall of a Lexan spindle that is attached to a torque meter and immersed in a beaker of ferrofluid. The beaker is centered inside a 2-pole or 4-pole motor stator winding, creating uniform or nonuniform rotating magnetic fields, respectively. The spindle rotates at a constant speed up to 100 rpm or is stationary in these measurements. Anomalous behaviors such as zero and negative magnetoviscosity are demonstrated and discussed. The experiments in Chapter 6 measure the magnetic torque on the inner wall of the spindle attached to the torque meter by filling a hollow spindle with ferrofluid. The spindle is centered inside the motor stator windings and exposed to the clockwise (CW) or counterclockwise (CCW) rotating magnetic fields. The
experiments in Chapter 7 measure the surface spin rate of a small floating plastic ball placed on the ferrofluid surface at a fixed location as a function of magnetic field parameters and position on the surface. When the rotating magnetic fields induce ferrofluid flows, the ball spins and this spin rate is determined using frame-by-frame video analysis.
Chapter 2
Magnetic and Fluid Properties

2.1 Magnetization Theory

Theoretical magnetization curves for ferrofluids are derived from the assumption that ferrofluids can be represented by a collection of individual, non-interacting, magnetic dipoles. The magnetization equation, also known as the Langevin relation for paramagnetic behavior, is found by using the energy required to rotate a magnetic dipole through an angle $\theta$ in a magnetic field. The derivation follows the form found in Zahn [2]. The torque exerted on a dipole by a magnetic field is:

$$T = \mu_o (m \times H) = \mu_o m H \sin \theta$$

(2.1)

where $m$ is the magnetic dipole moment, $H$ is the magnetic field, $\mu_o = 4\pi \times 10^{-7}$ H/m is the magnetic permeability of free space, and $\theta$ is the angle between the magnetic dipole and the field. This leads to the energy of the particle as:

$$W = \int_0^\theta T d\theta = m\mu_o H (1 - \cos \theta)$$

(2.2)

where $W$ is the work done to rotate the dipole. Although the dipole moment tends to align itself with the magnetic field, there is an additional thermal energy that disrupts this
behavior and provides a random spatial orientation. This can be described using Boltzmann statistics, allowing the number density of dipoles with the energy given by equation (2.2) to be written as:

\[ n = n_o e^{-W/kT} = n_o e^{-m\mu_o H_s (1 - \cos \theta)/kT} = n_o e^{-m\mu_o H \cos \theta/kT} \tag{2.3} \]

where we lump the constant energy contribution within the amplitude \( n_o \), which is the number density when the magnetic field is zero, \( T \) is the temperature of the dipoles in degrees Kelvin, and \( k = 1.38 \times 10^{-23} \) Joules/Kelvin is Boltzmann’s constant. Integrating over a sphere of magnetic dipoles of radius \( R \) and dividing by the volume gives the average number density of dipoles:

\[ N = \frac{1}{4 \pi R^3} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \int_{r=0}^{R} n_o e^{\alpha \cos \theta} r^2 \sin \theta dr d\phi d\theta = \frac{n_o}{\alpha} \sinh \alpha \tag{2.4} \]

where \( \alpha = m\mu_o H/kT \). Equation (2.3) now becomes:

\[ n = \frac{N\alpha}{\sinh \alpha} e^{\alpha \cos \theta} \tag{2.5} \]

From Figure 2.1 we see that all the dipoles in the shell over the interval \( \theta + d\theta \) contribute to a net magnetization, which is in the direction of the applied magnetic field:

\[ dM = \frac{mn}{4 \pi R^3} \cos \theta r^2 \sin \theta dr d\phi d\theta \tag{2.6} \]

so that the total magnetization due to all the dipoles within the sphere is:
\begin{equation}
M = \frac{m \alpha N}{2 \sinh \alpha} \int_{\theta=0}^{\pi} \sin \theta \cos \theta e^{\alpha \cos \theta} d\theta = mN \left[ \coth \alpha - \frac{1}{\alpha} \right] 
\end{equation}

(2.7)

Figure 2.1: All the dipoles at an angle \( \theta \) together have a net magnetization in the direction of the applied field [2].

Since each spherical ferrofluid particle of radius \( R_p \) has domain magnetization \( M_d \), the magnetic moment of each ferrofluid particles is:

\begin{equation}
m = \frac{4}{3} \pi R_p^3 M_d 
\end{equation}

(2.8)

For magnetite, \( \mu_o M_d \) is 5600 Gauss = 0.56 Tesla [1].

Using equation (2.8) in equation (2.7), the Langevin equation for paramagnetic behavior is:

\begin{equation}
\frac{M}{mN} = \frac{M}{\phi M_d} = \frac{M}{M_s} = L(\alpha) = \coth \alpha - \frac{1}{\alpha} 
\end{equation}

(2.9)
where $\phi$ is the volume fraction of magnetic solid to carrier liquid and surfactant and $M_s - \phi M_d$ is the saturation magnetization of ferrofluid which corresponds to all the dipoles being aligned with the magnetic field. The volume fraction can be obtained from equation (2.9), from measurement of the saturation magnetization $M_s$:

$$
\phi = \frac{M_s}{M_d}
$$

(2.10)

The Langevin equation is plotted as shown in Figure 2.2, for magnetic particles of various diameters, and has both low-field and high-field asymptotes given by:

$$
\lim_{\alpha \ll 1} L(\alpha) \approx \frac{\alpha}{3} = \frac{\pi \mu_o M_a H d^3}{18 kT}
$$

(2.11)

$$
\lim_{\alpha \gg 1} L(\alpha) \approx (1 - \frac{1}{\alpha}) = (1 - \frac{6 kT}{\pi \mu_o M_a H d^3})
$$

(2.12)

where $d = 2R_p$.

The low-field limit describes a linear relationship between the magnetization, $M$, and the magnetic field, $H$. The slope, $\chi$, is the magnetic susceptibility and is given as:

$$
\chi = \frac{M}{H} = \frac{\pi \mu_o M_a M_s d^3}{18 kT}
$$

(2.13)
The magnetic susceptibility describes the linear magnetic response shown by a material. A large value of $\chi$ corresponds to a strong magnetic material, while a small value of $\chi$ corresponds to a weak magnetic material. Free space has $\chi = 0$. The magnetic susceptibility is related to the magnetic permeability, $\mu$, by:

$$\mu = \mu_o (1 + \chi)$$  \hspace{1cm} (2.14)

Equation (2.13) can be rewritten as:

$$\chi = \frac{\pi}{18} \phi \frac{\mu_o M_j^2 d^3}{kT}$$  \hspace{1cm} (2.15)
Equations (2.13) and (2.15) imply an inverse dependence of $\chi$ on temperature. Shliomis proposed a correction to equation (2.15), claiming that dipole interactions must be included when the magnetic volume fraction is approximately 10% or greater [64], given as:

$$\frac{\chi(2\chi + 3)}{\chi + 1} = \frac{\pi \phi \mu_d M_d^2 d^3}{6kT}$$  \hspace{1cm} (2.16)$$

In most ferrofluids, there is a distribution of magnetic particle diameters, $d$. The minimum particle size can be calculated from magnetization measurements using the high-field asymptote from equation (2.12). The maximum particle size can be calculated using the low-field limit from equations (2.11), (2.15), or (2.16). For ferrofluids with volume fractions around 10% or greater, equation (2.16) is needed to determine $d$. It is important to note that the particles in the ferrofluid are composed of a magnetic particle, coated with a surfactant. The particle diameter, $d$, in the above equations refers to the magnetic component of the particle only, and not to the true physical diameter that includes the surfactant layer.

2.2 Magnetic Relaxation Theory

The magnetic relaxation equation with an incompressible, magnetically linear ferrofluid undergoing simultaneous magnetization, $\mathbf{M}$, and reorientation due to fluid convection at flow velocity $\mathbf{v}$ and spin angular velocity $\omega$ is [1]:

$$\frac{\partial \mathbf{M}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{M} - (\omega \times \mathbf{M}) - \frac{1}{\tau_{\text{eff}}} [\mathbf{M} - \chi \mathbf{H}] = 0$$  \hspace{1cm} (2.17)$$

where $\tau_{\text{eff}}$ is the effective relaxation time constant. The two mechanisms by which the particle may relax are Brownian motion, which is the physical rotation of the particle to align the magnetic moment with the magnetic field, and Neél relaxation, which is the
rotation of the magnetic moment to align with the magnetic field with no particle rotation. The characteristic time describing Brownian motion is:

\[ \tau_B = \frac{4\pi \eta R^3}{kT} \]  

(2.18)

where \( \eta \) is the dynamic viscosity of the ferrofluid and \( R = R_p + \delta \) is the radius of the magnetic particle, \( R_p \), and the surfactant layer, with thickness \( \delta \). The Neél relaxation time is:

\[ \tau_N = \frac{1}{f} e^{\left(\frac{KV}{kT}\right)} \]  

(2.19)

where \( f = 10^9 \) Hz is a typical frequency constant of Neél relaxation in magnetite, \( V = \frac{4}{3} \pi R_p^3 \) is the magnetic particle volume, and \( K = 23,000 \) Joules/m\(^3\) is the anisotropy constant of the particle for magnetite. The effective time constant is defined as:

\[ \frac{1}{\tau_{eff}} = \frac{1}{\tau_B} + \frac{1}{\tau_N} \Rightarrow \tau_{eff} = \frac{\tau_B \tau_N}{\tau_B + \tau_N} \]  

(2.20)

The viscous time constant that describes the time scale for the entire particle, \( R \), to rotate in the viscous fluid flow is:

\[ \tau_v = \frac{\rho R^2}{15\eta} \]  

(2.21)

where \( \rho \) is the ferrofluid density. For typical values of \( R_p = 5 \) nm, \( \delta = 2 \) nm, \( R = 7 \) nm, \( \rho = 1000 \) kg/m\(^3\), \( \eta = 0.005 \) Ns/m\(^2\) = 5 cP, \( T = 300 \) K, representative time constants are \( \tau_B \).
= 5.2µs, \( \tau_N = 18.3 \text{ ns} \), and \( \tau_v = 0.653 \text{ ps} \), which shows that \( \tau_v \ll \tau_H, \tau_N \). Therefore, the time for the particle to rotate in viscous fluid flows occurs instantaneously compared to the time for Brownian and Neél relaxation.

2.3 Demagnetization Theory

The previous analysis assumes the magnetic field, \( H \), is the field \( H_i \) inside the ferrofluid. However, in most experiments, the external magnetic field \( H_e \) applied to the ferrofluid differs from the internal magnetic field \( H_i \) due to demagnetization effects described by a demagnetization factor, \( D \), given by equation (2.22). The demagnetization field is due to effective magnetic charge induced on the surface of a magnetic material, with magnetization \( M \), that contributes a magnetic field that partially cancels the externally applied magnetic field

\[
H_i = H_e - MD
\]  

(2.22)

The demagnetization factor for magnetization measurements using a vibrating sample magnetometer (VSM) was determined by approximating the ferrofluid container to be an oblate ellipsoid with two equal major axes, both \( n \) times as long as the minor axes as seen in Figure 2.3.a. The applied field is assumed parallel to one of the major axes as seen in Figure 2.3.b. A calculated demagnetization factor can be determined using the equation from Bozorth [65]:

\[
D = 1 \left[ \frac{n^2}{(n^2 - 1)^{3/2}} \arcsin \frac{\sqrt{n^2 - 1}}{n} - \frac{1}{n^2 - 1} \right] 
\]  

(2.23)

A plot of equation (2.23) is given in Figure 2.4. The demagnetization factor summed over three orthogonal axes must equal 1. For instance, a spherical vessel has equal symmetry over all three Cartesian axes and thus a demagnetization factor of 1/3 in each Cartesian
direction. For the vessel used in the VSM measurements, $n = 2.4$ so that (2.23) gives $D = 0.211$.

![Diagram of Ferrofluid Sample](image)

Figure 2.3: (a) Ferrofluid container for the VSM experiments. (b) Applied field direction for the approximate oblate ellipsoid geometry.

![Graph of Demagnetization Factor for Oblate Ellipsoid](image)

Figure 2.4: Demagnetization factor $D$ vs. $n$, the major to minor axis ratio.
2.4 Ferrofluid Density Measurements

The measured room temperature ferrofluid densities, $\rho$, in Table 2.1 were determined by filling a container with a known volume of fluid and calculating the mass of the fluid by subtracting the empty container mass from the total mass. All of the density values fell within the range listed in the ferrofluid data sheets provided by Ferrofluidics Corp. The ferrofluid data sheet values for ferrofluids used in these experiments are listed in Appendix 1.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$\rho$ (g/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF1634 Isopar-M Ferrofluid</td>
<td>1.18</td>
</tr>
<tr>
<td>MSGW11 Water Based Ferrofluid</td>
<td>1.22</td>
</tr>
<tr>
<td>NF1273 Wax Ferrofluid</td>
<td>1.41</td>
</tr>
<tr>
<td>NBF1677 Display Ferrofluid (Fluorocarbon based)</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Table 2.1: Measured room temperature densities of ferrofluids obtained from Ferrofluidics Corp.

2.5 Ferrofluid Viscosity Measurements

The viscosities, $\eta$, of the ferrofluids in Table 2.2 with zero magnetic field were measured at room temperature using a Brookfield viscometer Model LVDV-I+. The recommended Brookfield procedure was used, using 500mL of ferrofluid in a 600mL beaker and the Brookfield calibrated stainless steel spindle LV1. There was no magnetic field applied for these measurements. Non-magnetic Shell Diala A transformer oil was used to verify proper operation of the viscometer. The manufacturer specifies the viscosity to be $\eta = 20$ cP.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$\eta$ (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer Oil (Shell Diala A)</td>
<td>18</td>
</tr>
<tr>
<td>NF1634 Isopar-M Based Ferrofluid</td>
<td>11</td>
</tr>
<tr>
<td>MSGW11 Water Based Ferrofluid</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 2.2: Measured viscosities of transformer oil and ferrofluids in zero magnetic field.
The viscosities of the Display Ferrofluid and the Wax Ferrofluid were not measured because there was not enough ferrofluid available to be used in the Brookfield viscometer. Note that in the following pages in all chapters, the company numbers are left off when referring to the ferrofluid (i.e. when the Isopar-M Based Ferrofluid is mentioned, it is referring to the NF1634 Isopar-M Based Ferrofluid above).

2.6 Magnetization Data

The magnetization, $M$, of the ferrofluids was measured using a Digital Measurement Systems (DMS) Vibrating Sample Magnetometer Model 880. Ferrofluids were placed in the DMS plastic sample containers whose dimensions are shown in Figure 2.3.a. These dimensions approximate an oblate ellipsoid with major to minor axis ratio of $n = 2.4$. Using equation (2.20), the demagnetization factor for these experiments is $D = 0.211$, which was used to calculate the internal magnetic field shown in magnetization curves of Figures 2.6-2.12. The ferrofluid volume was calculated using the measured mass of ferrofluid and the density, taken from Table 2.1. The volume of the container was not used as the ferrofluid volume as often the container was not completely filled with ferrofluid. However, the calculated ferrofluid volume and container volume differed at most by 5.6%, with $n = 2.26$, yielding a difference in $n$ of 0.14, and a $D$ of 0.219. This difference in $D$ was negligibly small, so a value of 0.211 was used for all experiments. The VSM measures the externally applied field in Oersteds and the magnetization in emu. In free space, $H = 1$ Oersted converts to $B = 1$ Gauss. The conversion for emu is

$$Gauss = \frac{\text{emu}}{\text{volume in cc}} \times 4\pi.$$  

2.7 Ferrofluid Langevin Curves

The externally applied field, $H_e$, was increased until the saturation magnetization, $M_s$, was reached. The external field was also applied in the negative direction to demonstrate that the ferrofluids do not exhibit hysteresis. This is due to the random orientations of the free magnetic particles in the carrier fluid, removing any memory from the fluid that would contribute to hysteresis. Trials were run for the Isopar-M ferrofluid (Figure 2.5),
the water based ferrofluid (Figure 2.6), and the Display ferrofluid (Figure 2.7). The Langevin curve was not measured for the Wax ferrofluid because some of the sample spilled out. The internal magnetic field $H_i$ differs from the external magnetic field $H_e$ by a factor MD. For these ferrofluids, the largest M reached is 421 Gauss, so with a $D = 0.211$, $MD \approx 90$ Gauss. For $H \gg 90$ Gauss, the plots in Figures 2.5-2.7 are approximately valid for abscissa being $H_i$ or $H_e$.

The saturation magnetization of each ferrofluid was determined by taking the magnetization value at the largest internal magnetic field, with the exception of the Wax Ferrofluid, whose saturation value was taken from the Ferrofluidics Corp. data sheet. The volume fraction of each ferrofluid was calculated using equation (2.10). The values are listed in Table 2.3.

![Isopar-M Ferrofluid graph](image)

Figure 2.5: Measured Langevin curve for Isopar-M ferrofluid at room temperature, $T = 299K$. 

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Figure 2.6: Measured Langevin curve for water based ferrofluid at room temperature, T = 299K.

Figure 2.7: Measured Langevin curve for the Display ferrofluid above room temperature, T = 323K.
<table>
<thead>
<tr>
<th>Ferrofluid</th>
<th>Largest Internal Field (Gauss)</th>
<th>$\mu_0M_s$ (Gauss)</th>
<th>Temperature (K)</th>
<th>$\phi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isopar-M</td>
<td>7913</td>
<td>421.3</td>
<td>299</td>
<td>7.52</td>
</tr>
<tr>
<td>Water Based</td>
<td>13,959</td>
<td>187.3</td>
<td>299</td>
<td>3.34</td>
</tr>
<tr>
<td>Wax</td>
<td>550</td>
<td></td>
<td></td>
<td>9.82</td>
</tr>
<tr>
<td>Display</td>
<td>7919</td>
<td>394.1</td>
<td>323</td>
<td>7.04</td>
</tr>
</tbody>
</table>

Table 2.3: Measured ferrofluid saturation magnetizations at largest internal field and calculated volume fractions.

### 2.8 Linear Region of the Langevin Curve

In order to determine magnetic susceptibility, the slope of the low-field linear region is needed. The Langevin curves in Figures 2.5-2.7 do not have enough precision in the low-field region to accurately determine the slope. For this reason, the low-field linear region was separately measured for the Isopar-M ferrofluid (Figure 2.8), the water based ferrofluid (Figure 2.9), the wax ferrofluid (Figure 2.10), and the Display ferrofluid (2.11). The slope was determined by linearly fitting the data using a least squares fit in Microsoft Excel. The magnetic susceptibility, $\chi$, and the $R^2$ values for the linear fit, are listed for each ferrofluid in Table 2.4. The $R^2$ value is the proportion of the total variability (variance) in the dependent variable that can be explained by the independent variables. The ideal value of $R^2$ is unity for a perfect straight line. In this low magnetic field range of 0-14 Gauss and magnetization up to 27 Gauss, the demagnetization correction field $MD$ up to $\approx 5.7$ Gauss is significant and must be used to obtain the proper value of magnetic susceptibility.

<table>
<thead>
<tr>
<th>Ferrofluid</th>
<th>$\chi$</th>
<th>$R^2$</th>
<th>Temperature, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isopar-M</td>
<td>2.181</td>
<td>0.9999</td>
<td>295</td>
</tr>
<tr>
<td>Water Based</td>
<td>0.651</td>
<td>0.9999</td>
<td>299</td>
</tr>
<tr>
<td>Wax</td>
<td>2.514</td>
<td>0.9999</td>
<td>300</td>
</tr>
<tr>
<td>Display</td>
<td>3.005</td>
<td>1.0</td>
<td>300</td>
</tr>
</tbody>
</table>

Table 2.4: Calculated ferrofluid magnetic susceptibility and $R^2$ values for the linear fits of magnetization measurements.
Figure 2.8: Measured Isopar-M ferrofluid magnetization linear region at room temperature, $T = 295K$.

Figure 2.9: Measured water based ferrofluid magnetization linear region at room temperature, $T = 299K$. 
Figure 2.10: Measured wax ferrofluid magnetization linear region at room temperature, $T = 300K$.

Figure 2.11: Measured Display ferrofluid magnetization linear region at room temperature, $T = 300K$.
2.9 Magnetic Particle Size

The minimum particle size for all ferrofluids was calculated by fitting the data to the Langevin curve high-field asymptote from equation (2.12). The maximum particle size for the water base ferrofluid was calculated using the low-field limit from equation (2.15). The other ferrofluids had volume fractions around 10%, so equation (2.16) was used to determine the maximum particle size. Table 2.5 lists the calculated minimum and maximum particle sizes for all ferrofluids.

<table>
<thead>
<tr>
<th>Ferrofluid</th>
<th>Minimum d (nm)</th>
<th>Maximum d (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isopar-M</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Water Based</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Wax</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>Display</td>
<td>13</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 2.5: Calculated ferrofluid magnetic particle diameter range.

2.10 Magnetic Time Constants

The Brownian, Neél, effective, and viscous time constants were calculated using equations (2.18) – (2.21), respectively. Table 2.6 lists calculated Brownian, effective, and viscous time constants for the Isopar-M and the Water Base fluid, since these are the only two ferrofluids whose viscosities were measured. The viscous time constant calculation assumes the surfactant adds an extra $\delta = 2$ nm to the particle radius, $R = R_p + \delta$ [1]. The Neél time constant was calculated for all ferrofluids. The time constants were calculated for a range of particle radii, using the minimum and maximum radii in Table 2.5, yielding a lower and upper bound range of time constants.

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$\tau_\theta$ (µs)</th>
<th>$\tau_N$ (ns)</th>
<th>$\tau_{\text{eff}}$ (ns)</th>
<th>$\tau_{\nu}$ (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isopar-M</td>
<td>14.1 – 20.0</td>
<td>48.7-482.2</td>
<td>48.5-470.8</td>
<td>0.402-0.507</td>
</tr>
<tr>
<td>Water Based</td>
<td>4.6-11.5</td>
<td>4.46-216.7</td>
<td>4.46-212.7</td>
<td>0.418-0.768</td>
</tr>
<tr>
<td>Wax</td>
<td>218.5 (max)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Display</td>
<td>378.3-6957.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.6: Calculated Brownian, Neél, effective, and viscous ferrofluid time constants.
Chapter 3

Torque Measurements as a Function of Magnetic Field Strength and Frequency

Analyses and measurements have shown anomalous behavior of ferrofluids in AC magnetic fields, whereby in linearly polarized or rotating magnetic fields the effective fluid viscosity can be increased or decreased and the ferrofluid can be pumped but the flow direction can reverse as a function of magnetic field amplitude, frequency, and direction. Analytical solutions for simple limiting cases show that the effective dynamic viscosity can be made positive, zero, or negative. These experiments investigate how the torque exerted by the ferrofluid on a spindle rotating at a constant speed varies as a function of magnetic field amplitude, frequency, and direction. These experiments particularly investigate the phenomenon of negative viscosity.

3.1 Experimental Setup

These experiments use a Brookfield viscometer Model LVDV-I+ as a torque meter. The viscometer spindle cylinder is lowered into the fluid and the viscometer exerts a torque to keep this spindle rotating at a constant speed. The viscometer measures the flow resistance to the counterclockwise rotating spindle caused by the fluid and reads out the torque as well as the fluid viscosity in centipoises (cP). Thus the torque values are proportional to the fluid viscosities. The range of measurable torque for the Brookfield viscometer is \(-6.73\mu\text{N-m} \text{ to } 67.3\mu\text{N-m}\). The rotating spindle can only rotate
counterclockwise. Note that negative torques have a range only 10% that of positive torques.

The standard Brookfield spindle LV1, is composed of stainless steel, which will act like an induction motor in the presence of an alternating magnetic field due to induced eddy currents. These currents in the magnetic field will cause additional magnetic torque on the spindle, which will confuse separation of ferrofluid viscous torque from induction motor torque. For this reason, an insulating Lexan (polycarbonate) spindle of diameter 25.5mm and length 122mm (Appendix 2) was used to ensure no eddy currents so that the measured magnetic fluid viscous torque was entirely from the ferrofluid.

The fluid was contained inside a 100mL beaker with inner diameter 38.5mm (Appendix 2), creating an annular gap of 6.5mm with the spindle. The fluid was filled inside the beaker with spindle in position so that the fluid height exactly matched the top of the stator winding, and the bottom of the beaker matched the lower end of the stator winding, so all of the ferrofluid volume was exposed to the magnetic field. The beaker was centered in either a three phase, 2-pole motor stator winding (uniform magnetic field) with inner bore of 78mm diameter (Appendix 2) or a 3 phase, 4-pole motor stator winding (non-uniform magnetic field) with inner bore of 115mm diameter (Appendix 2). Figure 3.1 shows the magnetic field lines for the three phase 2-pole uniform field and the 4-pole non-uniform field obtained by applying DC currents with appropriate ratio such as 1, -½, and -½ in each phase corresponding to t = 0 for a balanced three phase excitation [66]. Iron powder was sprinkled onto a piece of cardboard and the iron particles align along the net magnetic field. With a balanced three phase excitation to the three stator windings, this pattern rotates at angular speed equal to the electrical frequency of excitation. The experimental setup is shown in Figure 3.2 for the 2-pole stator winding. The magnetic fields in the motor stator windings were generated using sinusoidally varying currents with the appropriate phase differences to create magnetic fields that rotate clockwise or counterclockwise or with no phase difference to alternate along a constant direction. The distinction between uniform (2-pole stator) and non-uniform (4-pole stator) magnetic fields is important, as the magnetic force density in a ferrofluid is f
= \mu_o(M \cdot \nabla)H. In the 2-pole uniform field \( f = 0 \) while in the 4-pole non-uniform magnetic field \( f \neq 0 \).

With the spindle lowered into the ferrofluid, initial experiments set the viscometer to rotate the spindle at 100 rpm (counterclockwise) and to measure the ferrofluid torque on the spindle for various combinations of magnetic field amplitude and frequency. For both Figure 3.1: Magnetic field lines shown by iron powder in a 2-pole motor stator winding uniform field (left) and a 4-pole motor stator winding non-uniform field (right) [66].

uniform and non-uniform rotating magnetic field experiments, measurements were taken at frequencies of 1, 5, 10, 50 100, and 500 Hz with an input current of 0, 1, 2, 3, 4, and 5 Amps peak. In the 2-pole stator, this input current corresponds to a uniform external magnetic field of 0, 26, 52, 78, 104, and 130 Gauss rms respectively. In the 4-pole stator, these input currents correspond to non-uniform external magnetic fields of 0, 6, 12, 18, 24, and 30 Gauss rms respectively. These magnetic field measurements were made at the wall of the beaker (\( r \sim 12.5mm \)) in the absence of ferrofluid, and therefore reflect the external magnetic field that the ferrofluid "feels", and does not incorporate the demagnetizing factor from the ferrofluid geometry. Note that the magnetic field strength is lower in the 4-pole stator because the magnetic fields increase linearly with radius and the beaker radius is not very large. The fluid temperature was monitored during the experiment using a digital thermometer as the fluid magnetization depends on temperature and magnetic field through the Langevin magnetization equation (2.9).
3.2 Experimental Results: Torque vs. Magnetic Field Amplitude

These results plot the measured torque vs. magnetic field amplitude for various frequencies in the range of 1-500 Hz. For all ferrofluid torque measurements in this chapter, the spindle rotation rate was set to 100 rpm. For non-magnetic fluid measurements of transformer oil, the spindle rotation was 60 rpm.

3.2.1 Non-magnetic Fluid (Transformer Oil)

The torque vs. magnetic field amplitude at various frequencies was first measured for transformer oil, a non-magnetic fluid, to verify that the magnetic field had no effect on the experimental apparatus (Figure 3.3). This measurement used a 4-pole motor stator winding for a counterclockwise magnetic field, with a spindle rotation of 60 rpm.
3.2.2 Water Based Ferrofluid in a Non-Uniform Magnetic Field

The same experiment, with a spindle rotation of 100 rpm, was then repeated using the water based ferrofluid in the 4-pole stator, for a clockwise (Figure 3.4), counterclockwise (Figure 3.5), and alternating magnetic field (Figure 3.6). Figure 3.4 shows a torque decrease with increasing CW magnetic field amplitude, corresponding to a decrease in magnetoviscosity. A zero magnetoviscosity was not reached because the maximum magnetic field of 30 Gauss was too small. Figure 3.5 shows a torque increase with increasing CCW magnetic field amplitude, corresponding to an increase in magnetoviscosity. Figure 3.6 shows that with a linearly polarized alternating magnetic field there is no change in torque within experimental accuracy.
Figure 3.4: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 4-pole clockwise rotating magnetic field. The temperature varied between 24.6-25.9 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, in the same direction as spindle rotation, thereby lowering the torque required from the viscometer.

Figure 3.5: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 4-pole counterclockwise rotating magnetic field. The temperature varied between 22.4-24.2 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer.
Figure 3.6: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 4-pole alternating magnetic field. The temperature varied between 25.6-28.8 degrees Celsius. Within experimental accuracy, the torque was independent of magnetic field amplitude and frequency.

3.2.3 Isopar-M Ferrofluid in a Non-Uniform Magnetic Field

This experiment was then repeated with the Isopar-M ferrofluid in the 4-pole stator, for a clockwise (Figure 3.7), counterclockwise (Figure 3.8), and alternating magnetic field (Figure 3.9) with similar results as for the water based ferrofluid. Figure 3.7 shows a torque decrease with increasing CW magnetic field amplitude, corresponding to a decrease in magnetoviscosity. Again, a zero magnetoviscosity was not reached because the maximum magnetic field of 30 Gauss was too small. Figure 3.8 shows a torque increase with increasing CCW magnetic field amplitude, corresponding to an increase in magnetoviscosity. Figure 3.9 shows with a linearly polarized alternating magnetic field no change in torque within experimental accuracy.

3.2.4 Water Based Ferrofluid in a Uniform Field

Measurements were taken in the 2-pole stator for the water based ferrofluid in a clockwise (Figure 3.10), counterclockwise (Figure 3.11), and alternating magnetic field (Figure 3.12) with similar results as for a non-uniform rotating magnetic field. Some
Figure 3.7: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 4-pole clockwise rotating magnetic field. The temperature varied between 21.1-21.6 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, in the same direction as spindle rotation, thereby lowering the torque required from the viscometer.

Figure 3.8: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 4-pole counterclockwise rotating magnetic field. The temperature varied between 21.1-21.7 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer for 500Hz.
Figure 3.9: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 4-pole alternating magnetic field. The temperature varied between 21.3-21.6 degrees Celsius. Within experimental accuracy, the torque was independent of magnetic field amplitude and frequency.

trials contained fewer measurements for two reasons: the Brookfield viscometer is limited to torque ranges of -6.73 to 67.3 \( \mu \text{N-m} \) and the input current amplitude is limited at higher frequencies due to the increased inductive reactance of the motor stator. The higher amplitude CW magnetic fields in the 2-pole stator cause zero and negative torques in Figure 3.10 for frequencies of 50Hz and above. Figure 3.11 shows a torque increase with increasing CCW magnetic field amplitude, corresponding to an increase in magnetoviscosity. Unlike the null results in alternating non-uniform magnetic fields, Figure 3.12 shows a torque increase with increasing alternating magnetic field amplitude, corresponding to an increase in magnetoviscosity. This difference may be due to the increase in magnetic field strength.

### 3.2.5 Isopar-M Ferrofluid in a Uniform Magnetic Field

Measurements were taken in the 2-pole stator for the Isopar-M ferrofluid in a clockwise (Figure 3.13), counterclockwise (Figure 3.14), and alternating magnetic field (Figure 3.15) with similar results to a water based ferrofluid in section 3.2.4. The higher amplitude CW magnetic fields cause zero and negative torques in Figure 3.13 at 500 Hz.
Figure 3.14 shows a torque increase with increasing CCW magnetic field amplitude, corresponding to an increase in magnetoviscosity, except for 5Hz. Figure 3.15 shows a torque increase with increasing alternating magnetic field amplitude, corresponding to an increase in magnetoviscosity.

![Water Based Ferrofluid Graph](image)

Figure 3.10: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 2-pole clockwise rotating magnetic field. The temperature varied between 22.6-24.2 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was generally counterclockwise, in the same direction as spindle rotation, thereby lowering the torque required from the viscometer. The torque passes through zero to negative values for frequencies 50Hz and above, corresponding to zero and negative magnetoviscosities.

### 3.3 Experimental Results: Torque vs. Magnetic Field Frequency

This section takes the same measurements of section 3.2 and replots the torque vs. magnetic field frequency for various amplitudes in the range of 0-130 Gauss. The frequency axis is on a log scale for all figures.

#### 3.3.1 Non-magnetic Fluid (Transformer Oil)

The torque vs. magnetic field frequency at various amplitudes was measured for transformer oil, a non-magnetic fluid, to verify that the magnetic field had no effect on the experimental apparatus (Figure 3.16). This measurement used a 4-pole motor stator winding for a counterclockwise magnetic field.
Figure 3.11: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 2-pole counterclockwise rotating magnetic field. The temperature varied between 24.1-27.1 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer.

Figure 3.12: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 2-pole alternating magnetic field. The temperature varied between 27.3-29.5 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow at higher frequencies was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer.
Figure 3.13: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 2-pole clockwise rotating magnetic field. The temperature varied between 18.2-19.9 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, in the same direction as spindle rotation, thereby lowering the torque required from the viscometer. The torque passes through zero to negative values at 500Hz.

Figure 3.14: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 2-pole counterclockwise rotating magnetic field. The temperature varied between 21.0-22.8 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer, except at 5Hz which shows a decreasing torque at high magnetic fields.
Figure 3.15: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 2-pole alternating magnetic field. The temperature varied between 23.1-26.7 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer.

Figure 3.16: Torque vs. magnetic field frequency at various amplitudes for transformer oil, a non-magnetic fluid, in a 4-pole counterclockwise rotating magnetic field. For this experiment only, the counterclockwise spindle rotation rate was set to 60 rpm. The temperature varied between 25.2-26.2 degrees Celsius. Within experimental accuracy, the torque was independent of magnetic field amplitude and frequency.
3.3.2 Water Based Ferrofluid in a Non-Uniform Magnetic Field

The same experiment was then repeated using the water based ferrofluid in the 4-pole stator, for a clockwise (Figure 3.17), counterclockwise (Figure 3.18), and alternating magnetic field (Figure 3.19). Figure 3.17 shows a torque decrease with increasing CW magnetic field frequency, corresponding to a decrease in magnetoviscosity. A zero magnetoviscosity was not reached because the maximum magnetic field of 30 Gauss was too small. Figure 3.18 shows a torque increase with increasing CCW magnetic field frequency, corresponding to an increase in magnetoviscosity. Figure 3.19 shows that in an alternating magnetic field, the torque went up between 5 and 10 Hz and down for all other frequencies.

![Water Based Ferrofluid](image)

Figure 3.17: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 4-pole clockwise rotating magnetic field. The temperature varied between 24.6-25.9 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, in the same direction as spindle rotation, thereby lowering the torque required from the viscometer.

3.3.3 Isopar-M Ferrofluid in a Non-Uniform Magnetic Field

This experiment was then repeated with the Isopar-M ferrofluid in the 4-pole stator, for a clockwise (Figure 3.20), counterclockwise (Figure 3.21), and alternating magnetic field (Figure 3.22). Figure 3.20 shows in a CW magnetic field, a maximum torque at 50 Hz.
Figure 3.21 shows in a CCW magnetic field, a minimum torque at 10 Hz. Figure 3.22 shows in an alternating magnetic field, a minimum torque between 10-50 Hz.

![Water Based Ferrofluid](image)

Figure 3.18: Torque vs. magnetic field frequencies at various amplitudes for water based ferrofluid in a 4-pole counterclockwise rotating magnetic field. The temperature varied between 22.4-24.2 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer.

### 3.3.4 Water Based Ferrofluid in a Uniform Field

Measurements were taken in the 2-pole stator for the water based ferrofluid in a clockwise (Figure 3.23), counterclockwise (Figure 3.24), and alternating magnetic field (Figure 3.25). Figure 3.23 shows a torque decrease with increasing CW magnetic field frequency, corresponding to a decrease in magnetoviscosity. Zero and negative magnetoviscosity was reached at higher amplitude fields for frequencies of 50 Hz and higher. Figure 3.24 shows a torque increase with increasing CCW magnetic field frequency, corresponding to an increase in magnetoviscosity. Figure 3.25 shows a torque decrease with increasing alternating magnetic field frequency, corresponding to a decrease in magnetoviscosity.
Figure 3.19: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 4-pole alternating magnetic field. The temperature varied between 25.6-28.8 degrees Celsius. The torque went up between 5 and 10 Hz and down at all other frequencies.

Figure 3.20: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 4-pole clockwise rotating magnetic field. The temperature varied between 21.1-21.6 degrees Celsius. The maximum torque was at 50 Hz.
Figure 3.21: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 4-pole counterclockwise rotating magnetic field. The temperature varied between 21.1-21.7 degrees Celsius. The minimum torque was at 10 Hz.

Figure 3.22: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 4-pole alternating magnetic field. The temperature varied between 21.3-21.6 degrees Celsius. The minimum torque was between 10-50 Hz.
Figure 3.23: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 2-pole clockwise rotating magnetic field. The temperature varied between 22.6-24.2 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, in the same direction as spindle rotation, thereby lowering the torque required from the viscometer. The torque passes through zero to negative values for frequencies of 50 Hz and higher, corresponding to zero and negative magnetoviscosities.

Figure 3.24: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 2-pole counterclockwise rotating magnetic field. The temperature varied between 24.1-27.1 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer.
3.3.5 Isopar-M Ferrofluid in a Uniform Magnetic Field

Measurements were taken in the 2-pole stator for the Isopar-M ferrofluid in a clockwise (Figure 3.26), counterclockwise (Figure 3.27), and alternating magnetic field (Figure 3.28). Figure 3.26 shows a torque decrease with increasing CW magnetic field frequency, reaching a negative magnetoviscosity at 500 Hz. Figure 3.27 shows a torque increase with increasing CCW magnetic field frequency, corresponding to an increase in magnetoviscosity, except for higher amplitude fields at 5 Hz. Figure 3.28 shows a torque decrease with increasing alternating field frequency, corresponding to a decrease in magnetoviscosity.
Figure 3.26: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 2-pole clockwise rotating magnetic field. The temperature varied between 18.2-19.9 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, in the same direction as spindle rotation, thereby lowering the torque required from the viscometer. The torque passes through zero to negative values at 500Hz.

Figure 3.27: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 2-pole counterclockwise rotating magnetic field. The temperature varied between 21.0-22.8 degrees Celsius. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, in the opposite direction to spindle rotation, thereby increasing the torque required from the viscometer, except at 5Hz, which shows a decreasing torque at high magnetic fields.
3.4 Analysis of Experiments

The spindle rotating in the ferrofluid with zero magnetic field causes ferrofluid flow in the same direction as spindle rotation. In the presence of a rotating magnetic field, the ferrofluid flow profile changes, which changes the viscous shear stress on the spindle. Note that in a Newtonian fluid, the direction of shear stress is in the same direction as the velocity gradient at the spindle interface. However, because ferrofluids are a particle suspension, capable of sustaining anti-symmetric states of stress [1, 33], there is an additional contribution to the viscous shear stress due to particle spin velocity so that the viscous shear stress can reverse sign, to be discussed in greater detail in section 5.5. For all measurements, the change in viscous shear stress at the spindle due to magnetic-field-induced flow was opposite to the direction of magnetic field rotation, except occasionally at low frequencies around 1-5 Hz.

The viscometer uses the measured torque and converts it to a viscosity, based on the spindle type. Therefore the viscosity is directly proportional to the measured torque values. These ferrofluid measurements with rotating magnetic fields report viscometer
viscosity readings that are zero and negative. Such paradoxical readings occur when the magnetic-field-induced flow causes a change in viscous shear stress at the spindle that is in the same direction as the rotating spindle (counterclockwise) thus requiring less torque from the viscometer to turn the spindle; fooling the viscometer to read out a decreased viscosity. If the ferrofluid exerts a shear stress on the spindle that equals that necessary to turn the spindle at constant rate, no torque is required from the viscometer and it records a zero viscosity. The cylinder rotation is then entirely due to the shear stress from the magnetic-field-induced flow. A greater fluid shear stress requires the viscometer to reverse torque direction to maintain constant spindle rotation and the viscometer reads negative viscosity values. When magnetic-field-induced ferrofluid flow induces a change in viscous shear stress that is in the opposite direction to the spindle rotation (clockwise), more torque is required from the viscometer and it is fooled to think that the ferrofluid viscosity has increased.

Rotating magnetic fields can thus induce a rich variety of flows in ferrofluids, dependent on the magnetic field amplitude, frequency, and direction of rotation. The changes in viscous shear stress due to the magnetic-field-induced flow were greater for higher magnetic field amplitudes and frequencies. For linearly polarized alternating magnetic fields the torque increased with uniform magnetic field amplitude and generally decreased with magnetic field frequency. The phenomenon of “negative effective viscosity” is revealed to be no more than a magnetic-field-induced ferrofluid torque strong enough to overcome the viscometer torque.
Chapter 4

Torque Measurements as a Function of Spindle Rotation Rate

It was demonstrated with the experiments in Chapter 3 that the ferrofluid behavior is strongly dependent on the magneto-mechanical coupling. The experiments in Chapter 3 focused primarily on how the magnetic field amplitude and frequency affects torque, varying the magnetic field amplitude at a given frequency while keeping the spindle rotation speed constant. The experiments in this chapter focus primarily on how the mechanical component affects torque, varying the spindle rotation speed at a given magnetic field amplitude and frequency.

4.1 Experimental Setup

These experiments use the same setup as the experiments in Chapter 3, with the same spindle, beaker, and motor stator winding. The trials in these experiments use only the water based ferrofluid and only in the 2-pole motor stator winding (uniform fields). The 4-pole motor stator winding produces a magnetic field strength of only 30 Gauss rms at the beaker wall. Therefore, because the effects of the 4-pole magnetic field were much smaller, they were not investigated in these experiments. The reported measurements in this chapter used spindle rotation speeds of 20, 30, 50, 60, and 100 rpm. All magnetic field amplitudes are given in Gauss rms.
4.2 Non-magnetic Fluid (Transformer Oil) with no Magnetic Field

The torque vs. spindle rotation speed was first measured for transformer oil (Figure 4.1), a non-magnetic fluid, in the absence of a magnetic field. This experiment shows that the torque from the fluid on the Lexan spindle linearly increases with spindle rotation rate. This verifies that the viscosity of the transformer oil is constant, which should be the case for a Newtonian fluid. Because transformer oil is non-magnetic, the results of Figure 4.1 are independent of magnetic field.

![Figure 4.1: Torque vs. spindle rotation speed in the absence of a magnetic field. The torque increases linearly with spindle rotation speed, verifying a constant viscosity for this Newtonian fluid.](image)

Because the measurements of Figure 4.1 used the Lexan spindle rather than the calibrated Brookfield spindle and used a smaller container vessel rather than the required 600ml beaker, viscosity readings for the measurements of Figure 4.1 would not be accurate, although the torque values are accurate. To obtain a sense of the accuracy we calculate the estimated viscosity from the torque measurements in Figure 4.1 using viscous dominated Couette flow [67] to the Table 2.2 viscosity of 18 cP. The velocity profile for
an inner cylinder of radius \( r_o \) rotating at angular speed \( \omega_o \) (radians/second) and surrounded by fluid in an outer cylinder of radius \( r_i \) is:

\[
v_o(r) = \frac{\omega_o}{\left(\frac{r_i^2}{r_o^2}\right)^2 - 1} \left(\frac{r_i^2}{r} - r\right)
\] (4.1)

The viscous shear stress \( T_s \) at the spindle interface \( r = r_o \) is:

\[
T_s = \eta \frac{d v_o}{d r}(r = r_o) = -\eta \frac{\omega_o r_o^2}{r_i^2 - r_o^2} \left(1 + \frac{r_i^2}{r_o^2}\right)
\] (4.2)

where \( \eta \) is the viscosity of the fluid and \( d v_o/dr \) \( (r = r_o) \) is the shear rate at the spindle interface.

The torque on the spindle interface is:

\[
\Gamma = F r_o = T_s A r_o = T_s 2\pi r_o^2 L = -2\pi \eta L \frac{\omega_o r_o^2}{r_i^2 - r_o^2} \left(r_o^2 + r_i^2\right)
\] (4.3)

Using the values in the experiment of section 4.2 of \( r_o = 12.75 \text{ mm}, r_i = 21.65 \text{ mm}, L = 61 \text{ mm}, \omega_o = 100 \text{ rev/min} = 10.47 \text{ rad/s}, \text{ and } \Gamma = 39.21 \times 10^{-6} \text{ N-m}, \) the viscosity of the transformer oil was calculated to be 29cP. The difference from the measured value in section 2.5 of 18 cP is probably due to the 2.6 mm gap between the rotating inner cylinder and the bottom of the beaker. This adds an additional drag force that needs to be incorporated into equation (4.2) and is the reason why the current calculated value is greater than the measured value.
4.3 Experimental Results: Torque vs. Spindle Rotation Speed for Varying Magnetic Field Amplitudes

These results plot the torque vs. spindle rotation for various magnetic field amplitudes at a fixed magnetic field frequency. All experiments used a water based ferrofluid in a uniform rotating magnetic field.

4.3.1 Uniform Magnetic Field at 1 Hz

The same experiment was then repeated using the water base ferrofluid, for a 1Hz uniform clockwise (Figure 4.2) and counterclockwise (Figure 4.3) rotating magnetic field. Figure 4.2 and Figure 4.3 shows that the torque increases with spindle rotation speed and magnetic field amplitude, but with some slight nonlinear dependence on spindle rotation speeds.

![Figure 4.2: Torque vs. spindle rotation speed in a 1Hz 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field amplitude.](image)
Figure 4.3: Torque vs. spindle rotation speed in a 1Hz 2-pole counterclockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field amplitude.

4.3.2 Uniform Magnetic Field at 5 Hz
The same experiment was then repeated for a 5Hz uniform clockwise (Figure 4.4) and counterclockwise (Figure 4.5) rotating magnetic field. Figure 4.4 shows the torque increases with spindle rotation speed, but decreases for higher CW magnetic field amplitudes. Figure 4.5 shows the torque increases with the spindle rotation speed and CCW magnetic field amplitude.

4.3.3 Uniform Magnetic Field at 10 Hz
The same experiment was then repeated for a 10Hz uniform clockwise (Figure 4.6) and counterclockwise (Figure 4.7) rotating magnetic field. Figure 4.6 shows the torque increases with spindle rotation speed, but decreases with CW magnetic field amplitude. Figure 4.7 shows the torque increases with the spindle rotation speed and CCW magnetic field amplitude.
Figure 4.4: Torque vs. spindle rotation speed in a 5Hz 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases for higher magnetic field amplitudes.

Figure 4.5: Torque vs. spindle rotation speed in a 5Hz 2-pole counterclockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field amplitude.
Figure 4.6: Torque vs. spindle rotation speed in a 10Hz 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases with magnetic field amplitude.

Figure 4.7: Torque vs. spindle rotation speed in a 10Hz 2-pole counterclockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field amplitude.
4.3.4 Uniform Magnetic Field at 50 Hz

The same experiment was then repeated for a 50Hz uniform clockwise (Figure 4.8) and counterclockwise (Figure 4.9) rotating magnetic field. Figure 4.8 shows the torque increases with spindle rotation speed, but decreases with CW magnetic field amplitude. Figure 4.9 shows the torque increases with the spindle rotation speed and CCW magnetic field amplitude.

4.4 Experimental Results: Torque vs. Spindle Rotation Speed for Varying Magnetic Field Frequencies

This section takes the same data as section 4.3 and replots the torque vs. spindle rotation for various magnetic field frequencies at a fixed magnetic field amplitude. All experiments used a water based ferrofluid in a uniform rotating magnetic field.

![Water Based Ferrofluid](image)

Figure 4.8: Torque vs. spindle rotation speed in a 50Hz 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases with magnetic field amplitude.
Figure 4.9: Torque vs. spindle rotation speed in a 50Hz 2-pole counterclockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field amplitude.

4.4.1 Uniform Magnetic Field at 0 Gauss

The torque was measured for a 0 Gauss magnetic field (Figure 4.10). Figure 4.10 shows the torque increases with spindle rotation speed, and at a slightly greater than linear rate. This suggests the water based ferrofluid is slightly non-Newtonian with the property of shear-thickening.

4.4.2 Uniform Magnetic Field at 26 Gauss

The same experiment was then repeated for a 26 Gauss uniform clockwise (Figure 4.11) and counterclockwise (Figure 4.12) rotating magnetic field. Figure 4.11 shows the torque increases with spindle rotation speed, but decreases with CW magnetic field frequency. Figure 4.12 shows the torque increases with the spindle rotation speed and CCW magnetic field frequency.
Figure 4.10: Torque vs. spindle rotation speed in a 0 Gauss magnetic field. The torque increased with spindle rotation speed and demonstrated a slight shear-thickening behavior.

Figure 4.11: Torque vs. spindle rotation speed in a 26 Gauss 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases with magnetic field frequency.
4.4.3 Uniform Magnetic Field at 52 Gauss

The same experiment was then repeated for a 52 Gauss uniform clockwise (Figure 4.13) and counterclockwise (Figure 4.14) rotating magnetic field. Figure 4.13 shows the torque increases with spindle rotation speed, but decreases with CW magnetic field frequency. Figure 4.14 shows the torque increases with the spindle rotation speed and CCW magnetic field frequency.

4.4.4 Uniform Magnetic Field at 78 Gauss

The same experiment was then repeated for a 78 Gauss uniform clockwise (Figure 4.15) and counterclockwise (Figure 4.16) rotating magnetic field. Figure 4.15 shows the torque increases with spindle rotation speed, but decreases with CW magnetic field frequency. Figure 4.16 shows the torque increases with the spindle rotation speed and CCW magnetic field frequency.
Figure 4.13: Torque vs. spindle rotation speed in a 52 Gauss 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases with magnetic field frequency.

Figure 4.14: Torque vs. spindle rotation speed in a 52 Gauss 2-pole counterclockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field frequency.
Figure 4.15: Torque vs. spindle rotation speed in a 78 Gauss 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases with magnetic field frequency.

Figure 4.16: Torque vs. spindle rotation speed in a 78 Gauss 2-pole counterclockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field frequency.
4.4.5 Uniform Magnetic Field at 104 Gauss
The same experiment was then repeated for a 104 Gauss uniform clockwise (Figure 4.17) and counterclockwise (Figure 4.18) rotating magnetic field. Figure 4.17 shows the torque increases with spindle rotation speed, but decreases with CW magnetic field frequency. Figure 4.18 shows the torque increases with the spindle rotation speed and CCW magnetic field frequency.

4.4.6 Uniform Magnetic Field at 130 Gauss
The same experiment was then repeated for a 130 Gauss uniform clockwise (Figure 4.19) and counterclockwise (Figure 4.20) rotating magnetic field. Figure 4.19 shows the torque increases with spindle rotation speed, but decreases with CW magnetic field frequency. Figure 4.20 shows the torque increases with the spindle rotation speed and CCW magnetic field frequency.

Figure 4.17: Torque vs. spindle rotation speed in a 104 Gauss 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases with magnetic field frequency.
Figure 4.18: Torque vs. spindle rotation speed in a 104 Gauss 2-pole counterclockwise rotating magnetic field. The torque increases with spindle rotation speed and magnetic field frequency.

Figure 4.19: Torque vs. spindle rotation speed in a 130 Gauss 2-pole clockwise rotating magnetic field. The torque increases with spindle rotation speed, but decreases with magnetic field frequency.
4.5 Summary Analysis of Experiments

For zero and nonzero magnetic field amplitudes, the torque increased with spindle rotation speed. In addition, the increase was greater than a linear relation, showing that ferrofluids exhibit a slight shear-thickening behavior that increased with magnetic field amplitude and frequency. The same trends were seen in these experiments as those in Chapter 3, that the rotating magnetic fields change the ferrofluid flow profile and therefore cause a change in the viscous shear stress in the opposite direction to magnetic field rotation and whose magnitude increases with magnetic field amplitude and frequency.
Chapter 5  

Torque Measurements with a Stationary Spindle  

It was demonstrated with the experiments in Chapters 3 and 4 that the ferrofluid torque is strongly affected by the rotating spindle that is driving flow as well as imposed magnetic fields. In those experiments, it is impossible to separate the viscous effects on torque due to the rotating spindle from the magnetic field effects on torque. In order to better understand the magnetic field effects, the experiments in this chapter measure the ferrofluid flow and torque driven by the magnetic field alone by keeping the spindle stationary.

In addition, the experiments in Chapters 3 and 4 were limited to a maximum frequency of 500Hz. This is because the inductive reactance \( L\omega \) increases with radian frequency \( \omega \) and limits the current that can be supplied to the stator winding. By adding the appropriate capacitors, \( C \) (see Appendix 3) in series with the motor, a resonant circuit can be created so the capacitive reactance \( 1/(C\omega) \) cancels the inductive reactance when \( L\omega = 1/(C\omega) \), no longer limiting the current at higher frequencies. Using this procedure, the experiments in this chapter were able to reach a maximum frequency of 5 kHz. Higher frequencies were not used because the voltage across the motor terminals became too high and the power amplifier was in danger of being overloaded.

5.1 Experimental Setup  

These experiments use the same setup as the experiments in Chapters 3 and 4, with the same spindle, beaker, and motor stator winding. The trials in these experiments use the
water base ferrofluid and the Isopar-M ferrofluid, only with the 2-pole motor stator winding (uniform fields). The 4-pole motor stator winding produces a magnetic field strength of only 30 Gauss rms at the beaker wall, generating only a small effect on torque. A larger radius spindle and beaker was constructed to be used in the 4-pole motor stator winding so that the ferrofluid would be at a much larger radius in the beaker, and therefore be exposed to much larger magnetic fields. The larger radius spindle either wobbled when rotating or did not allow any significant change in torque when stationary, both not allowing for accurate data, so no measurements were made in non-uniform magnetic fields. Future work needs to test a compatible spindle in the larger non-uniform magnetic fields from the 4-pole motor stator winding.

5.2 Experimental Results: Torque vs. Magnetic Field Amplitude
These results plot the measured torque vs. magnetic field amplitude for various frequencies in the range of 5 Hz – 5 kHz. The spindle remained stationary for all measurements.

5.2.1 Water Based Ferrofluid
The torque vs. magnetic field amplitude was measured for the water based ferrofluid in a clockwise (Figure 5.1) and counterclockwise (Figure 5.2) rotating uniform magnetic field. Figure 5.1 shows a negative torque with magnitude that increases with increasing CW magnetic field amplitude. Figure 5.2 shows a positive torque that increases with increasing CCW magnetic field amplitude.

5.2.2 Isopar-M Ferrofluid
The torque vs. magnetic field amplitude was measured for the Isopar-M ferrofluid in a clockwise (Figure 5.3) and counterclockwise (Figure 5.4) rotating uniform magnetic field. Figure 5.3 shows a generally negative torque with magnitude that increases with increasing CW magnetic field amplitude. Since the spindle is stationary and therefore produces zero torque with no magnetic field, all torque values were negative, except at 5 Hz. Figure 5.4 shows a positive torque that increases with increasing CCW magnetic field amplitude, except at 5 Hz.
Figure 5.1: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 2-pole clockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing negative torque required from the viscometer. The torque reached negative values for all frequencies.

Figure 5.2: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 2-pole counterclockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the torque required from the viscometer.
Figure 5.3: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 2-pole clockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing negative torque required from the viscometer. The torque reached negative values for all frequencies except 5Hz.

Figure 5.4: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 2-pole counterclockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the torque required from the viscometer, except at 5Hz which shows a decreasing torque at high magnetic fields.
5.3 Experimental Results: Torque vs. Magnetic Field Frequency

Using the same data of section 5.2 this section plots the torque vs. magnetic field frequency for various amplitudes in the range of 0-130 Gauss. The frequency axis is on a log scale for all figures. The spindle remained stationary for all measurements.

5.3.1 Water Based Ferrofluid

The torque vs. magnetic field frequency was measured for the water based ferrofluid in a clockwise (Figure 5.5) and counterclockwise (Figure 5.6) rotating uniform magnetic field. Figure 5.5 shows a negative torque with magnitude that increases with increasing CW magnetic field frequency. Since the spindle is stationary and therefore produces zero torque with no magnetic field, all torque values were negative. Figure 5.6 shows a positive torque that increases with increasing CCW magnetic field frequency.

![Water Based Ferrofluid](image)

Figure 5.5: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 2-pole clockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing negative torque required from the viscometer. The torque reached negative values for all frequencies.
Figure 5.6: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 2-pole counterclockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the torque required from the viscometer.

5.3.2 Isopar-M Ferrofluid

The torque vs. magnetic field frequency was measured for the Isopar-M ferrofluid in a clockwise (Figure 5.7) and counterclockwise (Figure 5.8) rotating uniform magnetic field. Figure 5.7 shows a generally negative torque whose magnitude increases with increasing CW magnetic field amplitude. Since the spindle is stationary and therefore produces zero torque with no magnetic field, all torque values were negative, except at 5 Hz. Figure 5.8 shows a torque increase with increasing CCW magnetic field amplitude, except at 5 Hz.

5.4 Flow Observations and Analysis

While doing the experiments in this chapter with a stationary spindle, the surface flow was observed by sprinkling chalk dust on the ferrofluid surface. The flow at the fluid/spindle interface was observed to be in the same direction as the rotating magnetic field as shown in Figure 5.9.
Figure 5.7: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 2-pole clockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing negative torque required from the viscometer, causing a decreased magnetoviscosity. The torque reached negative values for all frequencies, except at higher fields for 5Hz.

Figure 5.8: Torque vs. magnetic field frequency at various amplitudes for Isopar-M Ferrofluid in a 2-pole counterclockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the torque required from the viscometer, except at 5Hz, which shows a decreasing torque at high magnetic fields.
These experiments indicate that there is a strong effect on the ferrofluid from the magnetic field. The magnetic field can induce ferrofluid flow and no additional mechanical force is needed from the rotating spindle. The torque behavior in these experiments is similar to the experiments in Chapters 3 and 4 - the changes in viscous shear stress due to the magnetic-field-induced flow increased with increasing magnetic field amplitude and frequency. It would be desirable to increase the magnetic field frequency even higher. It is hypothesized that above a critical frequency, the torque would then decrease with further increasing frequency. This critical frequency occurs around:

$$\Omega \tau_{\text{eff}} \approx 1$$  \hspace{1cm} (5.1)

where $\Omega$ is the magnetic field angular frequency and $\tau_{\text{eff}}$ is the effective magnetic relaxation time constant from (2.20). Since $\tau_{\text{eff}}$ is on the order of 5-500 ns, this means a magnetic field frequency of 2-200 MHz would be needed, much higher than the available experimental capability.

The spindle is shown in cylindrical coordinates in Figure 5.10:
Assuming the flow velocity is $\theta$-directed, the fluid shear stress $T_{\theta r}$ in the $\theta$ direction on the spindle surface which has a normal in the radial direction is given by [1, 33]:

$$T_{\theta r} = \eta \frac{d\nu_\theta}{dr} + \zeta \frac{d\nu_\theta}{dr} - 2\zeta \omega_z$$  \hspace{1cm} (5.2)

$$= (\eta + \zeta) \frac{d\nu_\theta}{dr} - 2\zeta \omega_z$$  \hspace{1cm} (5.3)

where $\nu_\theta$ is the $\theta$-directed ferrofluid velocity and $\omega_z$ is the $z$-directed ferrofluid spin velocity. The term $\zeta$ is the vortex viscosity, which in the infinite dilution limit, is given by [68]:

$$\zeta = \frac{3}{2} \eta \phi$$  \hspace{1cm} (5.4)
where $\phi$ is the ferrofluid volume fraction and $\eta$ is the fluid dynamic viscosity, defined in section 2.1 and section 2.2 in Chapter 2.

The first term in the fluid shear stress of equation (5.2) is the usual hydrodynamic Newtonian shear stress. The second two terms are the anti-symmetric contribution due to the suspension of magnetic particles in the fluid. In the case of the experiments in this Chapter, these two terms become significant due to the rotating magnetic field-induced-flow.

In a purely Newtonian fluid, the viscous shear stress only contains the first term in (5.2). For a CCW flow in the positive $\theta$ direction, the shear stress for a stationary spindle would be in the CCW direction, in the same direction as flow, causing the viscometer torque to become negative in order to keep the spindle stationary. For the ferrofluid, a CCW magnetic-field-induced flow is observed at the spindle/fluid interface in a CCW rotating magnetic field, but the viscometer torque is measured to be positive for the CCW magnetic field, as seen in Figures 5.2 and 5.4. The reason for this contradiction is that the ferrofluid has the two additional antisymmetric components of shear stress given in (5.2). In order to produce positive viscometer torque for a CCW flow with a stationary spindle, the shear stress would need to be in the CW direction, in the opposite direction of flow.

Recognizing that for CCW flow both $\frac{dv_\theta}{dr}$ and $\omega_z$ are positive, the condition for a shear stress in the opposite direction of flow is given by:

$$2\zeta \omega_z > (\eta + \zeta) \frac{dv_\theta}{dr} \quad (5.5)$$

This antisymmetric shear stress analysis shows that the torque measurements are compatible with observations and measurements.
Chapter 6

Torque Measurements Without a Free Surface

The experiments in Chapters 3-5 measured the torque on a spindle that was immersed in a beaker of ferrofluid. These experiments all had the ferrofluid surface free, exposed to the air. Rosensweig [1] argues that ferrofluid flow is completely driven by free surface effects and that without a free surface, there should be no flow, and for these stationary spindle experiments, therefore no torque. By completely filling a hollow spindle with ferrofluid so that there is no free surface, the torque was measured for a ferrofluid. In contradiction to Rosensweig’s conclusion, significant non-zero torques were measured.

6.1 Experimental Setup

These experiments use a similar setup as the experiments in Chapters 3-5, with the same motor stator windings. Since the hollow spindle is filled with ferrofluid, no beaker is necessary. The hollow spindle has an inner diameter of 19.5mm and hollow chamber length of 62mm, yielding a ferrofluid volume of 18.8 cm$^3$ (Appendix 2). The trials in these experiments use the water base ferrofluid and the Isopar-M ferrofluid within the 2-pole motor stator winding (uniform fields). No measurements were made in the 4-pole motor stator winding for the same weak magnetic field reasons discussed in Chapter 5.
6.2 Experimental Results: Torque vs. Magnetic Field Amplitude

These results plot the measured torque vs. magnetic field amplitude for various frequencies in the range of 5 Hz – 5 kHz. The spindle remained stationary for all measurements.

6.2.1 Water Based Ferrofluid

The torque vs. magnetic field amplitude was measured for the water based ferrofluid in a clockwise (Figure 6.1) and counterclockwise (Figure 6.2) rotating uniform magnetic field. Figure 6.1 shows a positive torque increase with increasing CW magnetic field amplitude. Figure 6.2 shows a negative torque with magnitude that increases with increasing CCW magnetic field amplitude. Note that for positive torques, the maximum measurable value is 63.7 \( \mu \)N-m, while for negative torques the maximum is –6.37\( \mu \)N-m.

![Water Based Ferrofluid](image)

Figure 6.1: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 2-pole clockwise rotating uniform magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the positive torque required from the viscometer with increasing amplitude.
6.2.2 Isopar-M Ferrofluid

The torque vs. magnetic field strength was measured for the Isopar-M ferrofluid in a clockwise (Figure 6.3) and counterclockwise (Figure 6.4) rotating uniform magnetic field. Figure 6.3 shows a positive torque increase with CW increasing magnetic field amplitude. Figure 6.4 shows a negative torque with magnitude that increases with increasing CCW magnetic field amplitude.

Figure 6.2: Torque vs. magnetic field amplitude at various frequencies for water based ferrofluid in a 2-pole counterclockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing the negative torque required from the viscometer with increasing amplitude.

6.3 Experimental Results: Torque vs. Magnetic Field Frequency

These results plot the torque vs. magnetic field frequency for various amplitudes in the range of 0-130 Gauss. The frequency axis is on a log scale for all figures. The spindle remained stationary for all measurements.
Figure 6.3: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 2-pole clockwise rotating uniform magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the positive torque required from the viscometer with increasing amplitude.

Figure 6.4: Torque vs. magnetic field amplitude at various frequencies for Isopar-M ferrofluid in a 2-pole counterclockwise rotating uniform magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing the negative torque required from the viscometer with increasing amplitude.
6.3.1 Water Based Ferrofluid

The torque vs. magnetic field amplitude was measured for the water based ferrofluid in a clockwise (Figure 6.5) and counterclockwise (Figure 6.6) rotating uniform magnetic field. Figure 6.5 shows a positive torque increase with increasing CW magnetic field frequency. Figure 6.6 shows a negative torque decrease with magnitude that increases with increasing CCW magnetic field frequency.

Figure 6.5: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 2-pole clockwise rotating uniform magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the positive torque required from the viscometer with increasing frequency.
Figure 6.6: Torque vs. magnetic field frequency at various amplitudes for water based ferrofluid in a 2-pole counterclockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing negative torque required from the viscometer with increasing frequency.

6.3.2 Isopar-M Ferrofluid

The torque vs. magnetic field strength was measured for the Isopar-M ferrofluid in a clockwise (Figure 6.7) and counterclockwise (Figure 6.8) rotating uniform magnetic field. Figure 6.7 shows a positive torque increase with increasing CW magnetic field frequency. Figure 6.8 shows a negative torque with magnitude that increases with increasing CCW magnetic field frequency.

6.4 Analysis of Experiments

These experiments indicate that without a free surface there is a significant torque from the ferrofluid viscous shear stress, and therefore a magnetic-field-induced flow. When compared to previous measurements in Chapters 3-5, these measurements follow the same trend - the effect on torque increases with magnetic field amplitude and frequency. However, there is one significant difference in these measurements with ferrofluid inside the spindle-- for the same rotating magnetic field direction, the change in viscometer torque is in the opposite direction to that when the ferrofluid is outside the spindle. For
Figure 6.7: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 2-pole clockwise rotating uniform magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was clockwise, thereby increasing the positive torque required from the viscometer with increasing frequency.

Figure 6.8: Torque vs. magnetic field frequency at various amplitudes for Isopar-M ferrofluid in a 2-pole counterclockwise rotating magnetic field. The change in viscous shear stress at the spindle due to magnetic-field-induced flow was counterclockwise, thereby increasing negative torque required from the viscometer with increasing frequency. The torque reached negative values for all frequencies.
instance, for the experiments in Chapters 3-5, a CW rotating magnetic field causes a negative torque with magnitude that increases with increasing magnetic field amplitude and frequency. The experiments in this chapter show that a CW rotating magnetic field causes a positive torque increase with increasing magnetic field amplitude and frequency. Although the ferrofluid flow cannot be observed inside the spindle, the measured torque is due to the change in shear stress on the inner spindle interface due to the magnetic-field-induced flow. Since the shear stress now acts on the inner spindle surface, whose normal is in the negative radial direction, the torque from the change in shear stress should be acting in the opposite direction to when the ferrofluid was outside the spindle. This is the reason for the difference in torque directions described above. This proves that a free surface is not necessary to induce ferrofluid flow.
Chapter 7
Spin Rate Experiments

In the previous chapters, the fluid flow was characterized through torque measurements, either at the spindle outer interface or without a free surface on the spindle inner interface. In this chapter, fluid flow on the surface of the ferrofluid will be characterized by measuring the spin rate of a floating plastic ball on the fluid surface as a function of radial position and magnetic field amplitude and frequency.

7.1 Experimental Setup

For these experiments, a small floating plastic ball with diameter 8mm (Appendix 2) was pierced with a needle, creating a central axis on which to spin, and the needle was attached to a toothpick with tape. The toothpick was held in place by a ring clamp attached to a ring stand, allowing the floating ball to be free to rotate in place at a fixed radius on the ferrofluid surface as seen in Figure 7.1. The ferrofluid was in a container of diameter 77mm (Appendix 2) and filled so the ferrofluid surface was at the top of the motor stator winding and the bottom of the container was at the bottom of the motor stator winding, so that all the ferrofluid was exposed to the uniform magnetic field. The applied magnetic field induced flow, causing a surface flow that caused the floating ball to spin in place, in the opposite direction to the magnetic field. The spinning ball was videotaped and later analyzed frame-by-frame to determine the spin rate as a function of radial position and magnetic field amplitude and frequency (Appendix 4). The maximum measurable spin rate was around 10 revolutions per second (rps). For spin rates higher than this, the video frame became too blurry to determine how fast the ball was spinning.
7.2 Experimental Results

All experiments used a water based ferrofluid in a uniform clockwise rotating magnetic field. The ball spin rate is always counterclockwise as shown in Figure 7.2. This is the same sense of ferrofluid flow around the spindle in Chapter 5.

7.2.1 Uniform Magnetic Field at 50 Hz

The CCW spin rate of the small floating plastic ball vs. magnetic field amplitude was measured for the water based ferrofluid in a CW rotating magnetic field at 50Hz (Figure 7.3).
Figure 7.2: Rotating magnetic field is CW and the floating ball spin is CCW.

![Diagram showing magnetic field direction and ball spin]

Figure 7.3: CCW spin rate of small floating plastic ball vs. magnetic field amplitude for the water base ferrofluid in a 50Hz uniform CW rotating magnetic field for various radial positions. The CCW spin rate increased and then decreased above a critical magnetic field amplitude. The spin rate went to zero at r = 30mm at a high enough magnetic field.

![Graph showing spin rate vs. magnetic field amplitude]
7.2.2 Uniform Magnetic Field at 100 Hz

The CCW spin rate of the small floating plastic ball vs. magnetic field amplitude was measured for the water based ferrofluid in a CW rotating magnetic field at 100 Hz (Figure 7.4).

Figure 7.4: CCW spin rate of small floating plastic ball vs. magnetic field amplitude for the water base ferrofluid in a 100Hz uniform CW rotating magnetic field for various radial positions. The CCW spin rate increased with magnetic field amplitude.

7.2.3 Uniform Magnetic Field at 500 Hz

The CCW spin rate of the small floating plastic ball vs. magnetic field amplitude was measured for the water based ferrofluid in a CW rotating magnetic field at 500 Hz (Figure 7.5).

7.2.4 Uniform Magnetic Field at 1 kHz

The CCW spin rate of the small floating plastic ball vs. magnetic field amplitude was measured for the water based ferrofluid in a CW rotating magnetic field at 1kHz (Figure 7.6).
7.2.5 Uniform Magnetic Field at 2 kHz

The CCW spin rate of the small floating plastic ball vs. magnetic field amplitude was measured for the water based ferrofluid in a CW rotating magnetic field at 2kHz (Figure 7.7).

Figure 7.5: CCW spin rate of small floating plastic ball vs. magnetic field amplitude for the water base ferrofluid in a 500Hz uniform CW rotating magnetic field for various radial positions. The CCW spin rate increased approximately linearly with magnetic field amplitude.

7.3 Analysis of Experiments

At lower frequency magnetic fields, the spin rate was less than the spin rate at higher frequencies. The observed flow at these lower frequencies lacks any coherent rotation and exhibits a pulsing quality. These spin rate measurements have similar character to Chapter 5 in that both the torque and ball spin rate increases with frequency. At higher frequencies, the spin rate begins to increase approximately linearly with magnetic field amplitude and the spin rate is approximately the same for all radii, indicating that the fluid moves with approximate rigid body motion.
Figure 7.6: CCW spin rate of small floating plastic ball vs. magnetic field amplitude for the water base ferrofluid in a 1kHz uniform CW rotating magnetic field. The CCW spin rate increased approximately linearly with magnetic field amplitude. The spin rate seemed to be the same for all radii, implying rigid body motion.

Figure 7.7: CCW spin rate of small floating plastic ball vs. magnetic field amplitude for the water base ferrofluid in a 2kHz uniform CW rotating magnetic field. The CCW spin rate increased approximately linearly with magnetic field amplitude. The spin rate seemed to be the same for all radii, implying rigid body motion.
Chapter 8

Conclusions

8.1 Summary of Measurements in Alternating and Rotating Magnetic Fields

Chapter 3 showed that a rotating magnetic field induces ferrofluid shear stress at the spindle in the opposite direction as the magnetic field rotation for a spindle surrounded by ferrofluid. The change in viscous shear stress from this magnetic-field-induced flow is in the opposite direction to the magnetic field, due to the opposite sign of the antisymmetric part of the shear stress. The magnetoviscosity of the ferrofluid can be increased or decreased as a function of magnetic field amplitude, frequency, and direction of rotation. Zero and negative magnetoviscosities were obtained when the shear stress on the spindle equaled or exceeded the viscometer torque that was necessary to maintain the spindle rotation at a constant speed. These measurements are believed to be the first measurements of a zero or negative magnetoviscosity for a ferrofluid, although a zero electroviscosity has been measured for a dielectric suspension in a rotating electric field [32]. The only experiments that used non-uniform magnetic fields are contained in Chapter 3 and they showed that there were no significant affects on torque due to the low magnetic field amplitudes in the central region of the 4-pole stator winding. Future experiments will be performed in higher amplitude non-uniform magnetic fields using a larger beaker with ferrofluid annulus in the outer region of the 4-pole stator winding where the magnetic field is much stronger.
Chapter 4 shows that for zero and nonzero magnetic field amplitudes, the torque increased with spindle rotation speed, but the increase was slightly greater than a linear relation, showing that ferrofluids exhibit a slight shear-thickening behavior. The same trends were seen in these experiments as those in Chapter 3, that the rotating magnetic fields change the ferrofluid flow profile and therefore cause a change in the viscous shear stress that increases with magnetic field amplitude and frequency.

Chapter 5 shows that there is a strong effect on the ferrofluid from the magnetic field alone, when the spindle is stationary. The viscous shear stress on the spindle was shown to have a Newtonian symmetric component due to the velocity gradient of the fluid and also two antisymmetric terms due to the suspension of magnetic particles in the fluid. The observed ferrofluid flow at the fluid/spindle interface was in the same direction as the rotating magnetic field. The shear stress on the spindle is in the opposite direction as the rotating magnetic field, and therefore opposite to the ferrofluid flow at the spindle, due to the negative antisymmetric component of shear stress due to spin velocity being greater than the contribution from the velocity gradient.

Chapter 6 measures the shear stress on the inside spindle interface by completely filling a hollow spindle with ferrofluid. The measurements indicate that there is indeed a shear stress on the spindle and therefore a magnetic-field-induced flow without a free surface. In addition, the changes in torque are in the opposite direction as those in Chapters 3-5 where the ferrofluid was outside the spindle.

Chapter 7 shows that the spin rate of a floating plastic ball on a ferrofluid free surface increases with magnetic field frequency with spin in the opposite direction to magnetic field rotation. For higher frequency magnetic fields, the spin rate increases approximately linearly with magnetic field amplitude, and is approximately independent of radial position on the surface, indicating that the ferrofluid surface moves with rigid body motion.
These experiments demonstrate that in rotating magnetic fields, ferrofluids can exhibit a rich class of flows that is strongly dependent on the magnetic field amplitude, frequency, and direction of rotation. There are still numerous further experiments that need to be performed in order to fully elucidate the behavior of ferrofluid flows in rotating magnetic fields.

### 8.2 Future Work

The next step in suggested future work is to compare theory with experimental results. This comparison would help to further refine the analytical and physical model and better understand the experiments. By fitting theoretical predictions to measurements, many physical parameters can be determined such as the vortex viscosity $\zeta$, spin viscosity $\eta'$, ferrofluid spin velocity $\omega_s$, and spin velocity boundary conditions. The theory in the thesis of Carlos Rinaldi [33] can be especially compared to uniform magnetic field measurements.

Other experiments that are currently in progress by other research students:

1) placing a plastic cylinder free to rotate in a beaker of ferrofluid in the presence of a rotating magnetic field and determining the spin rate and torque on this rotating cylinder as a function of the depth the cylinder is immersed in ferrofluid and magnetic field amplitude and frequency. These experiments will help determine how much of magnetic-field-induced ferrofluid flow is due to volume or free surface effects. Measurements should also be done with a large volume of ferrofluid that extends outside the magnetic field region so that the free surface is in a region with negligible magnetic field.

2) placing small nonmagnetic particles on the ferrofluid surface and determining the linear velocity $v_\theta$ on the ferrofluid surface as a function of radial position on the surface and magnetic field amplitude and frequency from video recording. The video is analyzed frame-by-frame to determine the linear velocity $v_\theta(r)$.
Other experiments that will be soon performed are:

1) Filling the hollow spindle with various volumes of ferrofluid with a free surface and determining if the torque measurements scale with the volume. If the flow is driven by the free surface, then the torque should be independent of ferrofluid volume. If the flow is driven by volume effects alone, then the torque should be directly proportional to the volume of ferrofluid. If the flow is driven by a combination of both, then the torque when the spindle is completely filled and therefore has no free surface should not scale with the rest of the torque measurements at lower volumes when there is a free surface. Torque measurements should be performed for stationary and rotating spindles.

2) Filling the hollow spindle with ferrofluid and then placing this spindle in a beaker of ferrofluid, so that ferrofluid is on the inside and outside of the spindle. It can then be determined how the torque varies from the inner and outer viscous shear stresses for stationary and rotating spindles.

3) Repeat measurements of this thesis but with a fixed solid annulus top so that there is no surface flow.

4) Spindle torque measurements should also be performed with beakers of ferrofluid that are on a platform free to rotate.

5) Repeat measurements in this thesis with an alternating magnetic field as well as with various ratios of combined alternating and rotating magnetic fields.

6) All measurements reported in this thesis should also be performed in a 4-pole non-uniform magnetic field but with magnetic field strengths greater than 100 Gauss rms. With the present 4-pole machine this can be achieved using a larger radius spindle. It is important that this spindle be balanced and not heavier than 5 oz. for proper viscometer operation.
7) All these measurements should be repeated for various spindle and surrounding container diameters.
References


Appendix 1

Ferrofluid Properties

The average properties of laboratory ferrofluids obtained from Ferrofluid Corp. are listed in supplied material safety data sheets as follows:

Manufacturer’s Name: Ferrofluidics Corporation
Address: 40 Simon Street, Nashua, NH 03061
Telephone: (603) 883-9800 (x212)
Chemical Name: Proprietary Product
Chemical Family: Colloidal Dispersion
Formula: Mixture

A1.1 Isopar-M Ferrofluid
Trade Name and Synonyms: EMG 900 Series (Isopar-M)

A1.1.1 Components
Magnetite: 3-15% by volume
Oil Soluble Dispersant: 6-30% by volume
Carrier Liquid: 55-91% by volume

A1.1.2 Chemical and Physical Properties
Boiling Point (degrees F): 401-491
Specific Gravity: 0.92 to 1.47
Vapor Pressure (mmHg): 1 at 100 degrees F
Percent Volatile by Volume: 55-91%
Vapor Density (air = 1): 6.4
Solubility in Water: negligible
Evaporation Rate at: < 0.1
Appearance and Odor: Black liquid, Mild odor

A1.2 Water Based Ferrofluid
Trade Name and Synonyms: MSG W11 (Water based)

A1.2.1 Components
Magnetite: 2.8-3.5% by volume
Water Soluble Dispersant: 2.0-4.0% by volume
Water: 92.5-95.2% by volume
Food Grade Fragrance: 0.05%
A1.2.2 Chemical and Physical Properties
Boiling Point (degrees F): 212
Vapor Pressure (mmHg): 17 at 20 degrees Celsius
Percent Volatile by Volume: 92.5-95.2%
Vapor Density (air = 1): < 1
Solubility in Water: complete
Appearance and Odor: Black liquid, no odor

A1.3 Wax Ferrofluid
Trade Name and Synonyms: NF 1273 (Wax)

A1.3.1 Chemical and Physical Properties
Melting Point (degrees Celsius): ∼70
Appearance: solid, liquid above ∼70 degrees Celsius
No other data was provided

A1.4 Display Ferrofluid
Trade Name and Synonyms: Display Cell-Ferrofluid (Magnetite particles in FC 77 DuPont Fluorocarbon)

A1.4.1 Components
Magnetite: 5-6% by volume
Oil Soluble Dispersant: 15-19% by volume
Fluorocarbon Carrier: 75-80% by volume
The volume % of magnetic fluid is about 7-8%

A1.4.2 Chemical and Physical Properties
Boiling Point (degrees F): 194-225
Specific Gravity: ∼2.1
Vapor Pressure (mmHg): 42 at 20 degrees Celsius
Percent Volatile by Volume: 75-80%
Vapor Density (air = 1): 14
Solubility in Water: none
Evaporation Rate at: > 1 (butyl acetate = 1) [4.3 x 10^-5 gm/cm²sec at 22 degrees C]
Appearance and Odor: Black, odorless liquid
Appendix 2
Experimental Parts

A2.1 Spindles

Figure A2.1: The solid Lexan (polycarbonate) spindle used for the torque measurements in Chapters 3-5. Only the bottom half of the spindle was immersed in ferrofluid (61 mm depth). The threaded inset on the top of the spindle was attached to the Brookfield viscometer by screwing it on to the viscometer fixture.
Figure A2.2: The solid Lexan (polycarbonate) spindle used for the torque measurements in Chapters 3-5. Only the bottom half of the spindle was immersed in ferrofluid (61mm depth). The threaded inset on the top of the spindle was attached to the Brookfield viscometer by screwing it on to the viscometer fixture.
Figure A2.3: The partially hollow Lexan spindle filled with ferrofluid used for the torque measurements in Chapter 6. The wall spindle thickness is 3mm, so the ferrofluid diameter is 19.6 mm. The top was attached to the Brookfield viscometer.
Figure A2.4: The partially hollow Lexan spindle filled with ferrofluid used for the torque measurements in Chapter 6. The wall spindle thickness is 3mm, so the ferrofluid diameter is 19.6 mm. The top was attached to the Brookfield viscometer.
Figure A.2.5: The large Lexan spindle referred to in section 5.1 that was incompatible with the Brookfield viscometer. The upper section of diameter D1 was solid while the lower section of diameter D2 was hollow, in order to reduce the weight of the spindle and to allow the option of filling with ferrofluid for additional experiments. Despite attempts to lower spindle weight and to balance for no wobble, this spindle would still not operate properly with the Brookfield viscometer.
Figure A.2.6: The large Lexan spindle referred to in section 5.1 that was incompatible with the Brookfield viscometer. The upper section of diameter D1 was solid while the lower section of diameter D2 was hollow, in order to reduce the weight of the spindle and to allow the option of filling with ferrofluid for additional experiments. Despite attempts to lower spindle weight and to balance for no wobble, this spindle would still not operate properly with the Brookfield viscometer.
A2.2 Containers

Figure A2.7: The glass ferrofluid container used for the torque experiments in Chapters 3-5. The container wall thickness is 2.40 mm. The spindle was centrally aligned inside the vessel with the bottom of the spindle cylinder 2.6 mm above the bottom of the container. The whole assembly was centered inside the motor stator windings.
Figure A2.8: The glass ferrofluid container used for the torque experiments in Chapters 3-5. The container wall thickness is 2.40mm. The spindle was centrally aligned inside the vessel with the bottom of the spindle cylinder 2.6 mm above the bottom of the container. The whole assembly was centered inside the motor stator windings.
Figure A2.9: The ferrofluid container, a 300mL glass beaker, used for the spin rate experiments in Chapter 7. The container wall thickness is 3.2 mm. The container fit snugly in the 2-pole motor stator winding.
Figure A2.10: The ferrofluid container, a 300mL glass beaker, used for the spin rate experiments in Chapter 7. The container wall thickness is 3.2 mm. The container fit snugly in the 2-pole motor stator winding.
A2.3 Motor Stator Windings

Figure A2.11: The 2-pole motor stator winding used in the experiments in Chapters 3-7 to create uniform rotating magnetic fields. The casing thickness is 2.3mm.
Figure A2.12: The 2-pole motor stator winding used in the experiments in Chapters 3-7 to create uniform rotating magnetic fields. The casing thickness is 2.3mm.
Figure A2.13: The 4-pole motor stator winding used in the experiments in Chapters 3 to create nonuniform rotating magnetic fields. The casing thickness is 2.8mm.
Figure A2.14: The 4-pole motor stator winding used in the experiments in Chapters 3 to create nonuniform rotating magnetic fields. The casing thickness is 2.8mm.
A2.4 Plastic Ball

Figure A2.15: The floating plastic ball used in the experiments in Chapters 7 to measure the spin rate using frame-by-frame video analysis. The Y ball marking was used in order to visually determine the number of revolutions the ball made in a given time.
Figure A2.16: The floating plastic ball used in the experiments in Chapters 7 to measure the spin rate using frame-by-frame video analysis. The ball was pierced with a needle that was taped to a toothpick to hold the ball in a fixed radial position while still allowing it to spin.
Appendix 3

Motor parameters and Magnetic field excitation

A3.1 Motor parameters (2-pole)

Figure A3.1: The Y winding configuration for the three phase 2-pole motor stator windings. Each winding has its own inductance L and resistance R.

<table>
<thead>
<tr>
<th>Terminal</th>
<th>R (Ω)</th>
<th>L (mH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B</td>
<td>6.3</td>
<td>15.77</td>
</tr>
<tr>
<td>B-C</td>
<td>6.4</td>
<td>16.17</td>
</tr>
<tr>
<td>C-A</td>
<td>6.0</td>
<td>15.72</td>
</tr>
</tbody>
</table>

Table A3.1: Measured resistance R and inductance L values for the 2-pole motor stator winding at 1 KHz.
| R₁ + R₂ = 6.3 Ω | L₁ + L₂ = 15.77 mH |
| R₂ + R₃ = 6.4 Ω | L₂ + L₃ = 16.17 mH |
| R₃ + R₁ = 6.0 Ω | L₃ + L₁ = 15.72 mH |

| R₁ = 2.95 Ω | L₁ = 7.66 mH |
| R₂ = 3.35 Ω | L₂ = 8.11 mH |
| R₃ = 3.05 Ω | L₃ = 8.06 mH |

At higher frequencies, the impedance from the inductance of the windings becomes large as \( Z_L = j\omega L \), thus limiting the current delivered to the windings. To fix this, a capacitor was connected in series to each winding so that resonance can occur:

\[
Z = R + j \left( \omega L - \frac{1}{\omega C} \right) \equiv R, \text{ since } \omega L = \frac{1}{C\omega} \rightarrow \omega^2 = \frac{1}{LC}
\]

Figure A3.2: Adding a capacitor in series to each phase of the motor stator winding in order to achieve resonance and increase available current to the motor.
Figure A3.3: 2-pole motor stator windings with capacitors in series to achieve resonance.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>13.2 µF</td>
<td>3.3 µF</td>
<td>827 nF</td>
<td>132 nF</td>
</tr>
<tr>
<td>C₂</td>
<td>12.5 µF</td>
<td>3.1 µF</td>
<td>781 nF</td>
<td>125 nF</td>
</tr>
<tr>
<td>C₃</td>
<td>12.6 µF</td>
<td>3.1 µF</td>
<td>786 nF</td>
<td>126 nF</td>
</tr>
</tbody>
</table>

Table A3.2: Calculated capacitor values for a 2-pole motor stator winding necessary to achieve resonance at various frequencies.
A3.2 Motor parameters (4-pole)

Since the inductor and resistor values are approximately equal for each winding phase, they can be averaged so that the Y winding connection has equal values of L and R on each terminal branch:

![Diagram of Y winding configuration](image)

R = 1.8 Ω (at 1 kHz)
L = 4.43 mH (at 1 kHz)

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>22.87 μF</td>
<td>5.72 μF</td>
<td>1.43 μF</td>
<td>229 nF</td>
</tr>
</tbody>
</table>

Table A3.3: Calculated average capacitor values for a 4-pole motor stator winding necessary to achieve resonance at various frequencies.
A3.3 Protocol for Magnetic Field Excitation

Figure A3.5: Setup for motor stator winding excitation. The function generators generate voltage sine waves with controllable amplitude, frequency, and phase as dual inputs to the power amplifier. The current is then amplified and sent to the motor stator windings through the connector box. The two minus terminals of the power amplifier are grounded, grounding one winding of the motor. The capacitors to achieve resonance are connected in series with the motor terminals through the connector box.
Figure A3.6: Setup for motor stator winding excitation. The function generators generate voltage sine waves with controllable amplitude, frequency, and phase as dual inputs to the power amplifier. The current is then amplified and sent to the motor stator windings through the connector box. The two minus terminals of the power amplifier are grounded, grounding one winding of the motor. The capacitors to achieve resonance are connected in series with the motor terminals through the connector box.

**Motor Stator Winding excitation protocol**

1) Set the function generators for sinusoidal current at the desired frequency and amplitude on both. Set the time phase difference to + or –60 degrees. Since the motor stator windings are a Y connection (120 degrees out of phase in space), a 60 degree time phase difference is needed to generate rotating magnetic fields. Whether it is +60 or –60 degrees determines if the field is CW or CCW. A 0 degree phase difference creates a linearly polarized alternating magnetic field.
2) Check the direction of the rotating magnetic field using a compass. The direction the compass needle rotates is the direction the magnetic field is rotating.

3) Adjust the current amplitude by adjusting the gain on the power amplifier.

4) The current is measured by breaking the circuit at the connector box with a Fluke multimeter and measuring the rms current.

5) The magnetic field was measured with a gaussmeter at the beaker wall (where the ferrofluid would be located) in a beaker without ferrofluid for a range of currents. The magnetic field increased linearly with current. Therefore, by recording the current supplied to the motor stator winding on each trial, the magnetic field amplitude is known for that trial. The incorporation of the demagnetizing factor for the ferrofluid was not done.

6) The magnetic field rotation speed is the same as the frequency of the waveforms supplied from the function generator. This frequency can be changed by manually changing it on the function generator.
Appendix 4

Protocol for Spin Rate Video Analysis

A4.1 Video Analysis Protocol

The spin rate data of Chapter 7 was obtained through video analysis. The steps taken to obtain the measured values are as follows:

1) A “Y” is drawn on the floating plastic ball used in the experiment.

2) A video is taken of the experiment, using a Sony DCR–TRV900, camcorder at a specific magnetic field amplitude, frequency, and rotation direction by adjusting winding current amplitudes and phase. The floating ball was placed at a specific radius.

3) The camcorder is connected to a Personal Computer using a S-video cable.

4) Using the program Ulead VideoStudio 4.0, the video is transferred to the PC (see Figure A3.1).

5) The video clip is added to the “clipboard” with the “load video” button then dragged to the “storyboard.”

6) The clip is then put into timeline mode using the “storyboard/timeline” toggle switch.

7) The position of the “Y” is noted at a certain time in the video.

8) The video is then played frame by frame. The video frame rate was 29.797 fps, both before and after transfer to the PC. The frame time is 0.0334 seconds.

9) Once the position of the “Y” is the same as the noted position, the number of rotations and the change in time is noted.

10) The spin rate is calculated by (# of rotations / change in time).

11) Repeat steps 7-10, twice, with a different starting position and a different number of rotations in order to verify reproducibility.

12) The three values are then averaged to find the average spin rate for the experiment.
13) Repeat steps 1-12 for other amperage values, frequencies, and ball radial position.

Figure A4.1: Ulead VideoStudio 4.0 typical screen with appropriate buttons.