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Sensing Gyroscopic Properties of Rotating Magnetic Nanoparticles in Solution

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SENSING GYROSCOPIC PROPERTIES OF ROTATING MAGNETIC NANOPARTICLES IN SOLUTION

by

Brian Gerald Krug

A Dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering and Computer Engineering Western Michigan University June 2016

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A new sensor using magnetic nanoparticles and rotating magnetic fields has been developed. By spinning the nanoparticles in a rotating magnetic field, it is feasible to infer angular position and inertia if an external force is applied to the system. The nanoparticles are treated as a multitude of miniature gyroscopes whose overall effect can be combined as one single gyroscope. Two sensors were built to test the feasibility, both containing Fe3O4 nanoparticles.

The typical input current was 250 milliamps. When the sensor deviated from its magnetic axis by a small angle, the input current changed between 1 and 2 milliamps from the maximum input current Nanoparticles immersed in water had a more dramatic response than those suspended in toluene. The response was not completely predictable as some interactions during a disturbance were not accounted for. The sensor was effective if the angle changes are at 100 Hz or slower frequencies. When the sensor was returned to its original starting state at the end of a test, the output did not always return to the starting state output. This was attributed to not driving the
magnetic nanoparticles hard enough into saturation.

The proposed sensor design is simple to construct, easy to control, and its position is easy to obtain. The output is predictable and has a relatively useful bandwidth for most portable applications. It has environmental limitations and low signal constraints, but both can be overcome with better materials and filtering techniques.
ACKNOWLEDGMENTS

I would like most of all to thank my Wife, Jane, and both of my daughters, Lillian and Ava, without whose support, patience and attitude I would never have started this program. My parents are no longer with me, but have also always supported my path to higher education.

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Last, I would like to thank Mike Blowers, my former supervisor at Parker Hannifin. Mike encouraged me to pursue this degree in spite of work pressure and also helped me with the idea of this dissertation.

Brian Gerald Krug
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<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>$B_0$</td>
<td>Magnetic Field</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
</tr>
<tr>
<td>D</td>
<td>mass-spring displacement</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
</tr>
<tr>
<td>I</td>
<td>Inertia</td>
</tr>
<tr>
<td>$I_c$</td>
<td>Current</td>
</tr>
<tr>
<td>K</td>
<td>Boltzman’s constant</td>
</tr>
<tr>
<td>$k_{sp}$</td>
<td>Spring constant</td>
</tr>
<tr>
<td>L</td>
<td>Angular momentum</td>
</tr>
<tr>
<td>M</td>
<td>magnetization amplitude</td>
</tr>
<tr>
<td>M</td>
<td>mass</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electromechanical Systems</td>
</tr>
<tr>
<td>Q</td>
<td>Charge</td>
</tr>
<tr>
<td>R</td>
<td>radius</td>
</tr>
<tr>
<td>T</td>
<td>time</td>
</tr>
<tr>
<td>$U_o$</td>
<td>Magnetic permeability</td>
</tr>
<tr>
<td>V</td>
<td>Hydrodynamic volume (equivalent to nanoparticle volume)</td>
</tr>
<tr>
<td>X</td>
<td>position</td>
</tr>
<tr>
<td>A</td>
<td>angular acceleration</td>
</tr>
<tr>
<td>H</td>
<td>Viscosity</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>Theta – angle between the magnetic moment and imposed magnetic field</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
</tr>
<tr>
<td>$\omega$</td>
<td>ohmega – angular velocity of particle on axis</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Precession angular velocity</td>
</tr>
<tr>
<td>$\mathcal{N}$</td>
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CHAPTER 1

BACKGROUND AND MOTIVATION

1.1 Introduction

Maintaining a common reference is something all people do when standing, or walking or even sleeping. It is important to know which way is up and to rely on our senses to accurately indicate when there is a change in orientation. A gyroscope can artificially sense this affect by detecting angular acceleration. This paper describes gyroscopic properties with a new application of spinning nanoparticles. Nanoparticle research has been focused on medical applications where power and cost are not driving limitations. In order to be a practical sensor, power, size and cost are to be minimized. Medical uses range from detecting the concentrations of substances in blood [1] to fighting cancer. Many methods and limitations have been discovered or developed to spin magnetic nanoparticles in various forms. This dissertation investigates many of these methods and introduces new improvements to produce a better solution for a magnetic nanoparticle gyroscopic sensor.

The most important feature of a gyroscopic sensor is the ability to sense inertia. Gyroscopic inertia is the ability of a rotating object to resist being tilted [2]. They are used in many applications ranging from stability motion control to navigational aids. There are several different types of gyroscopes and not all are based on constant rotation. Early
inventions included a simple flywheel or a spinning top which are both physical objects rotated at a significant speed. The objects maintains their orientation while the vessel around them moves. These gyroscopes, while simple, are large, use significant power, and wear, causing a drift in measurements. More modern discoveries have led to laser, fiber-optic and Mico-Electro-Mechanical Systems (MEMS) based gyroscopes. One method that is particularly useful in portable applications is the MEMS gyroscope because of its size and minimal power consumption. However it is not an actual gyroscope in the convention sense. It does not spin like most other gyroscopes but instead it vibrates or torsions like a tuning fork. The idea of a nanoparticle based gyroscopic sensor combines the standard convention of a spinning mechanical gyroscope with modern ferrous based nanoparticle research to create a magnetic nanoparticle based gyroscopic sensor.

Many of today’s navigational gyroscopes are constructed using a gimbal or pivoting support in which a motorized axis spins. A spinning object will resist torque applied against its axis orientation due to an external force. An indirect result of an external force is a “wobbling” off the main axis. Any external force is linearly counteracted by inertia as momentum is conserved. The external force is turned into an opposite and apposing force as the gyroscope rotates 180°. Between the direct and 180° apposing force, the 90° orientation of the rotating nanoparticle does not have a canceling force, and momentum results in a motion at right angles to applied torque, referred to as precession. Without any external force, precession cannot occur. Mechanical based
gyroscopes require bearings and a motor, are difficult to manufacture on a miniature scale, and require a significant amount of power to continuously run.

A similar technology more closely related to a nanoparticle based gyroscope was experimented on in the military in the early 1960s [3]. This was referred to as a magnetic induction gyroscope. This instrument had no parts that were constantly moving, but did have moveable parts. By applying AC and DC currents in a source and signal windings, and adding an additional pickup coil around a magnetic core, changes in orientation would result in changes in the currents imposed on the pickup coil. Because of limited movement, it did not wear out quickly. This may have satisfied the need for the navy, but is still too large, complicated to construct and power hungry for portable applications.

One of the first attempts at eliminating friction and mechanical rotation in gyroscopes was accomplished using lasers. In the 1980’s laser gyroscopes [4] became popular although the concept of using light instead of motors to detect rotation dates back to the early 1900s. These gyroscopes had no moving parts but relied on precise measurements of the phase differences between two beams of light when driven on countercyclical paths. Laser gyroscopes were still expensive, relatively large and required significant power and not a good solution for handheld electronics. Lasers have become cheaper and smaller since the 1980s but were still not competitive with the nano-solutions in research today.

The next technology that has dominated the gyroscopic sensor world is Micro Electromechanical Systems or MEMS. These gyroscopes are based on a micro structure
that performs similar to a tuning fork. Any acceleration causes a capacitive change which can be measured and interpreted by a microprocessor. These sensors are small, fairly complicated to manufacture and require little power. They are sensitive to vibration/noise. New sensors have been developed that are stiffer making them less sensitive to linear acceleration and only susceptible to angular acceleration. This method requires a precise measurement of capacitance, require a large initial investment to fabricate and have already been incorporated into most portable applications.

A spinning magnetic nanoparticle based gyroscope is similar to a MEMS gyroscope in that it is based on a large scale effect on a micro or nano scale objects. By using nano-sized unbounded nanoparticles floating free in a solution, the effects of a single nanoparticle can be multiplied by thousands of times, allowing more precision of measurement. The technology to rotate the nanoparticles only requires two coils and two alternating current (AC) correctly phase shift aligned. Like the classic or laser gyroscope, this gyroscope is based on a disturbed rotating objects to detect acceleration. The proposed method of inducing the nanoparticle spin is important to keep the nanoparticles spinning in the same plane to maximize the bulk effect of all nanoparticles. Relatively simple construction, low cost, and low power can allow this emerging technology to someday compete with the widely popular MEMS technology used today. As MEMs devices get smaller and more integrated, they become fragile and more sensitive to electromagnetic thermal interference. Reliability and ruggedness are two qualities that increase the life of a sensor. MEMS sensors contain small intricate parts. If
a large shock or electrostatic discharge should bend or break one of these parts, the sensor is rendered inoperative. The magnetic nanoparticle based sensor reduces these issues. Because of the simplicity and ruggedness of the design, high shock or discharges may scramble the nanoparticles in solution, but as long as a rotating field can still be generated, the sensor can supply information about orientation. This is particularly important for military and for use in dangerous environments where replacement or repair is not quick, easy or even possible.

1.2 Research Goals

The objective of this research is prove the feasibility of a new type of gyroscopic sensor. The sensor is based on Iron oxide nanoparticles which are attracted to magnetic fields. First, a theoretical model will be used to estimate the magnitude and speed of the rotating magnetic fields. Next, a model is framed to predict the behavior of the rotating nanoparticles when exposed to an external force, resulting in precession.

After the models are defined, an experimental setup is proposed to validate the models. This will include a tolerance study as wide ranges of signals are required. Several variables are considered when attempting to optimize the sensor. Many more variables are kept constant and are left as a prospect for future research. Finally, all anomalies are noted and either explained or identified for further research.
A patent for this technology will be filed by the Western Michigan University. This is the beginning of an emerging technology. The results of this dissertation should show that this is a viable technology to be used in portable applications in the near future.
CHAPTER 2

PERTINENT LITERATURE

2.1 Spinning Nanoparticles, Gyroscopic Sensors, and Rotating Magnetic Fields

The concept of a magnetic nanoparticle based gyroscopic sensor is a culmination of ideas from different disciplines. Nanoparticle research is relatively new and has been conducted primarily in the medical field to isolate and treat disease. This includes the use of rotating magnetic nanoparticles. Many methods and limitations have been discovered when trying to rotate these nanoparticles. Each involves the physics of rotating or alternating external magnetic fields. When combining the lessons of these topics, a practical gyroscope must have advantages over existing gyroscopic technology, especially when dealing with portable, low power applications.

Gyroscopic devices have been around a long time and are used in aviation, military and space guidance systems, automotive and consumer devices. Newer and more profitable technologies have been focused on the consumer market where cellphones, drones and wearables are all available with some gyroscopic capability.
2.1.1 Rotating Magnetic Nanoparticles

Recent popularity of nanoparticle and nano-machine research was guided by the medical field. Nanoparticles can be moved, rotated and held steady remotely using magnetic fields. This technology makes treatment of diseases much safer as procedures require less invasive surgery and exposure to bacteria while providing more accurate and localized remedies. This research has been applied in medical applications for both treatment and analysis. Topics range from detecting the concentrations of substances in blood [1] to fighting cancer. Many methods and limitations have been discovered or developed to spin magnetic nanoparticles in various forms.

Why nanoparticles instead of micro or milliparticles? They are the smallest nanoparticles that are fairly simple to produce but of the proper size for practical medical use. They range in size from a few nanometers to hundreds of nanometers in diameter. They are smaller than a typical biological cell and comparable in size to viruses [5]. This allows them to be transported through the bloodstream or absorbed in the body without causing clotting, or permanent deposits. The popularity of nanoparticles in medical research has made them easily available and inexpensive for sensor research.

Nanoparticles can be manipulated with magnetic fields on the order of a millitesla, but magnetic field generators cannot be simply implanted into a patient’s body. Improvised Magnetic Resonance Imaging (MRI) machines are very powerful and have been considered as a means to guide and monitor injected magnetic nanoparticles [6].

8
Magnetite ($\text{Fe}_3\text{O}_4$) and the more stable form maghemite ($\text{Fe}_2\text{O}_3$) are the most common forms of magnetic nanoparticles available. Widely available and sometimes goes by the name “loadstone” [23]. A chunk of mined magnetite is shown in Figure 2.1. Magnetite is used in the experiments referenced in this dissertation. Pure Iron in metallic form could be used, but exposure to water would erode it into oxyhydroxide (rust) [5]. This is a problem in the medical industry, but not a limitation for a sensor where contact with water can be controlled.

![Figure 2.1. Large Piece of Magnetite](image)

Smaller nanoparticles around 10 nanometers in diameter in a solution maintain their relative position and orientation even in the presence of gravity [7] because of Brownian relaxation. Random motion and collisions keep the nanoparticles distributed and prevents settling [8]. Present research applications include drug carriers where magnetic nanoparticles are coated with a substance for transport. These nanoparticles range from 50 to 500 nm. MRI contrast agents (used to identify the path nanoparticles), and hypothermia mediators (used to spin and heat localized areas to destroy cells), are generally 5 to 50 nm in diameter [9].
When exposed to a magnetic field, magnetic nanoparticles in solution are free to align to the orientation of the field, similar to iron filings when placed on a surface around a magnetic. Shaking the surface a bit (to overcome surface friction), results a picture of the magnetic field potentials [10] as shown in Figure 2.2.

![Figure 2.2. Iron Filings Oriented Around a Bar Magnet][1]

The key to rotating the nanoparticles is to continuously change the field and keep the nanoparticles magnetic moment aligned. In order to accomplish this, a torque must be applied to the nanoparticle by the field. If both the field and nanoparticle’s magnetic moment are aligned, no torque can result [12]. There has to be some lag in order for there to be motion. The torque needs to overcome the viscous friction and thermal agitation of the fluid. Thermal agitation becomes more pronounced when dealing with very small nanoparticles which have been exploited as a means to treat and destroy cells
by raising the local temperature [13]. The relationship between phase lag and viscosity of the solution and angular speed [14] is shown in equation 1.

\[ \sin(\theta) = (6\eta) \frac{\omega}{M B_0} \]  

(1)

Where \( \theta \) is the angle between the magnetic moment and the imposed magnetic field, \( \eta \) is the viscosity of the fluid, \( \omega \) is the angular velocity, \( M \) is the magnetization amplitude, and \( B_0 \) is equivalent to \( \mu_0 H \). Finally, \( H \) is the rotating magnetic field intensity \( H_0 \cos(\omega t) \) [14]. This is the form of Gilbert’s equation for spinning magnetic nanoparticles which is a subset of the Fokker-Plank equation [14]. The Fokker-Plank equation describes dynamics of a nanoparticle including local heating affects. The solution to this equation has been used to determine the breakdown frequencies and magnitude of magnetic field energy needed to keep the magnetic nanoparticles spinning and the phase lag less than 90°. Once the lag grows greater than 90°, the nanoparticles can start experiencing unstable behavior or even a reversal of direction [13]. Research conducted on these equations has shown that there is a linear correlation between magnetic field strength and breakdown frequency. Phase lag is however independent of the magnetic nanoparticle concentration and not affected by the sample volume [13]. It is interesting to point out that unlike typical spinning toy tops which continue to spin after torque is applied, spinning magnetic nanoparticles do not continue to spin after the imposed magnetic field is removed. Similar to a child’s spinning top spinning in water, the inertial spinning is dramatically reduced by the frictional drag forces [8].
The concept behind rotation magnetic nanoparticles is similar to that of a rotary motor and can be controlled like a synchronous machine [7]. There are two methods to control this rotation. One is to use alternating magnetic fields and the other is by using rotation magnetic fields. When considering which is appropriate for a sensor, several factors must be considered. These include torque, complexity and signal quality.

First to be considered is torque. When spinning magnetic nanoparticles, it has already been shown that the maximum spinning frequency is dependent on magnetic field strength. This is determined at the point when the phase angle between the magnetic field and magnetic moment is at 90°. This also the point at which there is maximum torque. So this topic can really be changed to which method provides a greater magnetic field. Research has shown that magnetic field magnitude [15]. This effect does not vary much over frequency. Rotating magnetic field were successfully used to rotate nanoparticles from the upper nanometer range to the lower micrometer limits. This however is acceptable when accuracy or smooth motion is not a requirement, which is not the case for a nanoparticle based gyroscopic sensor.

Next, the complexity of a system that rotates magnetic nanoparticles can be compared to that of one that alternates them. A better definition of both methods is necessary. Alternating nanoparticles, have only one of two vectors, like the poles of a stationary magnet. As the nanoparticle aligns with the orientation, the orientation flips. This motion is rather “jerky” and can be compared to that of a DC motor. To generate alternating fields, only two Helmholtz coils are needed [15]. Two coils of equal radius,
separated by a distance equal to the radium of a coil, produce a uniform magnetic field between and inside the coils. A diagram of the alternating configuration is shown in Figure 2.3. The currents in the coils would be setup so as to produce fields at either 0° or 180° alignment, resulting in a push-pull force as the nanoparticles transition to angles between the two angles.

![Helmholtz coil](image)

*Figure 2.3. Alternating Field Coil Setup*

A rotated nanoparticle is one where the magnetic field creates a field vector to which the nanoparticle’s magnetic moment is constantly aligned to, or is slightly lagging. Its direction is constantly controlled while it rotates, like the hour hand of a clock. This is similar to the operation of an AC induction motor. Similar to a multi-pole motor, multiple winding are needed to create a smoothly rotating field. At a minimum two sets of two coils are needed, or a total of four coils. Ideally they would be setup as 2 sets of helmholts coils so as to produce the most uniform fields as shown in Figure 2.4.
The last factor to consider when creating a gyroscopic sensor is signal quality. Because alternating magnetic fields produce more phase lag, they are simpler to implement; it is the preferred method for magnetic manipulation [15]. The ability to control the angle of magnetic nanoparticles and prevent jitter or even reverse spins is crucial for a gyroscopic sensor. Research has been conducted to directly observe nanoparticles spinning under rotating or alternative magnetic fields. This has proven difficult for spherical nanoparticles [14]. Multiple nanoparticles have been used, fused, and coated to allow clear indication of rotation. The results from these experiments has shown a higher sensitivity to rotating magnetic fields [13] which is why, despite the higher complexity and higher power requirements, that rotating nanoparticles is preferred for a gyroscopic sensor.
2.1.2 Gyroscopes as Sensors

How do gyroscopes work and how are they used as sensors? Gyroscopes have been around for a long time. Foucault coined the name in 1855 in an experiment that showed that the earth rotated [6]. The theory behind gyroscopes is simple, although the physics are complicated. Any spinning object will maintain its orientation until acted upon by an external force. The most common example of this is demonstrated with a spinning bicycle wheel suspended from the ceiling by a single string tied to one side of its axel, Figure 2.5

![Spinning Bicycle Wheel](image)

*Figure 2.5. Spinning Bicycle Wheel*

Two rotations are noted in Figure 2.5. Because an external force is acting on the spinning wheel, namely gravity, a rotation perpendicular to the spinning rotation results. This spinning is known as precession which is simply a change in the orientation of the rotational axis of a rotating object [16]. This is a one feature important to the operation
of a magnetic nanoparticle based gyroscope. The theory portion of this dissertation will
detail how precession will be used to extract motion information, but a brief explanation
of precession is detailed next.

Although it appears like a magic trick, the bicycle tire shown in Figure 2.5 is not
tipping over because of angular momentum. A force exerted on a nanoparticle (mass)
will result in acceleration. That acceleration will continue forever or when counteracted
by another force. If a force is exerted on the top of the wheel in Figure 2.6 to the right
due to gravity (point A), that force is preserved at that point. But that point is moving
around the wheel.

At the same time, a similar force is exerted on a point on the bottom of the wheel
to the left (point B), due to tipping of the wheel. That point is also in motion around the
wheel. These forces are preserved on the points as they travel around the wheel. As the
points approach the midpoint up/down the wheel, the directions of the acceleration work
together (points C and D) resulting in a rotation of precession. When the nanoparticle
accelerations reach opposite points on the wheel (top point reaches the bottom and visa-
versa), the forces cancel.

Similar to a spinning top which appears to defy gravity until its spin slows down,
the forces incurred by gravity are cancelled by angular motion. If the right side of the
rotating bicycle tire were suddenly supported, precession would be eliminated as there
would be no forces to be added/canceled as the wheel spins. Gravity is one force to cause
precession.
The first Gyroscope to receive a patent was developed in 1905 in Germany. It was developed to assist in the navigation to the North Pole [2]. This gyroscope was known as the Kiel Gyro compass and the original company founded on this product is still around today, partnered with Raytheon. The real success of this compass was in using a spinning disc which experienced precession due to the Earth’s rotation. This allowed a more accurate measurement of “true north” unlike magnetic based compasses, which pointed to magnetic north. Similar to the gyroscope examined in this dissertation, the Gyro compass was filled with oil to help resist the axis from re-orientation with the non-precessed direction. This allowed the user to orient the compass to “true north” where it would no longer require as much torque to spin. This compass was limited in East-West travel as the compass would experience more error as the motion direction could counter-act with the Earth’s spin, eliminating the precession.

Recent attempts at making an accurate, simple gyroscope focused on eliminating all moving parts. These devices are actually more accurately “inertial” sensing machines
as gyroscopes are defined as operating on a spinning object [11]. The magnetic induction gyroscope is an example of this. A paramagnetic material is exposed to a magnetic field. When the whole system rotates, currents are induced into coils which are then translated as angles [9]. AC and DC Fields are required to set the initial conditions. A second instrument described as a gyroscope without moving parts is what has revolutionized angular sensing. There are many different kinds of MEMS inertial sensors as this has been an exciting research subject in nanotechnology. These include capacitive, optical, piezoresistive and tunneling technologies. Capacitive sensing is the most common technology exploited in most cellphones and consumer inertial devices [16]. Tiny etched metal rods are flexible enough to twist and bend when an external force is applied. These rods are setup interlaced like a comb, resulting in a capacitive change which can be correlated as an angle change or acceleration. Expensive and difficult to produce when first introduced, but high volume and manufacturing improvements have made these sensors hard to beat. Figure 2.7 shows an Analog Devices MEMS gyroscopic sensor (part number ADXRS290BCEZ) that sells for under $20. It measures 5.8 mm x 4.5 mm and requires less than .05 watts of power.

Figure 2.7. MEMS Gyroscope
2.1.3 Rotating Magnetic Fields

Methods have already been developed to rotate magnetic nanoparticles in industry. Figure 2.7 shows multi-domain and single domain magnetic particles. To limit this dissertation’s scope, only single domain magnetic nanoparticles are considered. This means that the magnetization does not vary across the nanoparticle [18].

![Multi domain and Single domain magnetic particles](image)

Figure 2.8. Magnetic Domains

One method commonly used in research is a simple setup of two insulated conductors oriented perpendicular to each other with a container of a single magnetic nanoparticle placed above [19]. Each conductor is subjected to an electric current, 90° out of phase, as shown in Figure 2.9. One single magnetic nanoparticle would ideally be suspended in place. This would be a stable point as the rotating magnetic field would tend to pull any magnetic object toward each wire. As the current in each wire approaches zero during the AC cycle, the nanoparticle would be aligned and attracted to the wire in a conducting portion of the AC cycle. This cycle repeats, resulting in a rotating nanoparticle, held in place above the intersection.
If more than one magnetic nanoparticle is present, they will be pulled together at the center. To allow free movement of the nanoparticles, an insulating, low friction barrier would be placed between the nanoparticles and the wires. The low friction barrier can be a non-magnetic fluid in the container. However, the nanoparticles would not be completely free to spin in the fluid because they are drawn to the wall of the container containing the fluid, closest to the intersection of the wires.

A second method used by researchers employs Helmholtz coils [20]. Helmholtz coils are relatively simple ways to produce an even distribution of magnetic fields, and can also be used to minimize interference from external magnetic fields. Two sets of coils are required as shown in Figure 2.4. The sets of opposing coils are supplied with alternating currents that are 90° out of phase. This will produce the smooth rotation needed for a proper gyroscopic motion. Helmholtz coils require that the distance between the coils equal the radius of the coils. Advantages include the uniform field...
produced between the coils and relative simplicity of the configuration. Disadvantages include the relative size of the coils and spacing, which are not always conducive for a portable sensor.
CHAPTER 3

THEORETICAL BACKGROUND

3.1 Derivation of Torque, Gyroscopic Motion and Rotating Magnetic Field Strength

There are several key principles that have been developed that can be applied to the design and analysis of a nanoparticle based inertial sensor. First, a proven method to consistently and reliably spin thousands of nanoparticles in unison has been accomplished in the medical industry. There are many limitations to these methods which will be explored in this chapter. Second, gyroscopes have been used as navigational and inertial aids for over a century. The equations of precession motion and forces are needed to understand where sensory data can be derived. Third, a better understanding of MEMS inertial sensors, the industry leading type of inertial sensor, can help identify the weaknesses and strengths of a nanoparticle based sensor. Last, many methods to generate magnetic fields have been developed to control magnetic objects. These will be researched to determine the best method to control and extract data from a magnetically induced sensor. This research combines the research on spinning nanoparticles with the methods of generating rotating magnetic fields and focuses them on retrieving inertial information to formulate a final inertial sensor design.
3.1.1 Nanoparticle Torque

Not all gyroscopic sensors rely on a spinning object, but by definition, a gyroscope is defined by Webster’s dictionary are as follows: “a wheel or disk mounted to spin rapidly about an axis and also free to rotate about one or both of two axes perpendicular to each other and to the axis of spin so that a rotation of one of the two mutually perpendicular axes results from application of torque to the other when the wheel is spinning and so that the entire apparatus offers considerable opposition depending on the angular momentum to any torque that would change the direction of the axis of spin” [11]. The key elements from this definition exploited in this sensor is spin and torque. There have been several proven methods to spin magnetic nanoparticles. They could be spun in air, in a vacuum, or in a liquid. This dissertation will focus on a sensor which spins the nanoparticles in liquid. As will be shown, this simplifies the sensor at the expense of signal strength and energy loss.

Magnetic nanoparticles were chosen simply because their orientation can be controlled with magnetic fields. Specifically, Magnetite (Fe₃O₄) was chosen because it is superparamagnetic, meaning the nanoparticles do not have a magnetic moment in the absence of a magnetic field. Once an external field is applied, the nanoparticles become magnetized [1]. Magnetite is readily available immersed in water or toluene. Magnetite and maghemite are the most commonly used nanoparticles in medical applications [5].
Raw iron would be preferred, but it quickly converts to iron oxide (rust) when exposed to water.

When applying a torque to spin magnetic nanoparticles in a liquid, ideally they would spin with very little energy and coast to a stop when the field is removed. The torque required can be calculated as the cross product between the magnetic moment of the nanoparticle \( m \), and the magnetic field vector \( B \) as shown in (3.1).

\[
\tau = m \times B
\]  \hspace{1cm} (3.1)

But there are many factors working against this torque. Experiments and simulations of nanoparticle motion in a fluid have shown that there is a viscous drag on the nanoparticles. This is given at a first approximation in (3.2).

\[
\tau = -6 \eta V \omega
\]  \hspace{1cm} (3.2)

This torque is calculated using \( \eta \), the viscosity of the fluid, \( V \), the hydrodynamic volume of the nanoparticle, and \( \omega \), the angular velocity [8]. This equation is known as the Stokes-Einstein relation for small Reynold’s number nanoparticles [8]. A small Reynold’s number refers to the fact that the nanoparticles in fluid will have negligible inertial rotation after torque is removed]. In medical applications, there is often other substances fused with the nanoparticle, so the hydrodynamic volume would be less than the total volume. This is however not the only apposing torque.

The last significant drag apposing rotation is due to the random collisions of the nanoparticle with the molecules in the fluid, which increases with temperature. This has
been derived from the Einstein-Smoluchowski diffusion equation as shown in [8] and [3.3].

$$\tau = -\sqrt{12k\eta VT}\mathcal{N} \quad (3.3)$$

This equation has some elements from (3.2) as viscosity is a function of thermal effects. This equation also contains $T$, temperature, $k$, boltzman’s constant, and $\mathcal{N}$, a white noise force to account for the random collision of nanoparticles in the fluid. Summing all of the relevant torques (3.4) results in the final estimation of total torque on a spinning magnetic nanoparticle suspended in a fluid due to an external magnetic field:

$$\tau = M \times B - 6\eta V\omega - \sqrt{12k\eta VT}\mathcal{N} \quad (3.4)$$

Equation (3.4) is valid for alternating-sinusoidal or rotating magnetic fields [19]. This is a form of the Stochastic Langevin equation which has no closed form solution [8].

If the field and the moment were exactly aligned, no motion would result, as shown by eq (3.1). The cross product equation includes a sine of the angle between the moment and the magnetic field. If the angle is zero, the torque is zero. In contract, if the angle is 90°, the torque is at a maximum. If the angle should exceed 90°, there is a threat of backward rotation, eliminating all gyroscopic effects. The angle between the moment and torque depends on the phase lag dependent on the size of the nanoparticle and strength of the magnetic field. For nanoparticles less than four nanometers in diameter, Néel relaxation dominates where the internal magnetic moment relaxation or recovery time dominates the phase lag time. If the nanoparticles are greater than four
nanometers, Brownian motion dominates. In this case, nanoparticle rotation in the fluid determines the phase lag time [6]. The size barrier where the dominating relaxation method reigns varies up to ten nanometers for some research [21]. Magnetite, has a single domain magnetization (magnitude of \( m \)) of 446 kA/m [6]. Research has shown that the phase lag is independent of magnetic nanoparticle concentration and therefore is not dependent on the sample volume [15].

There is a maximum frequency, where synchronization between the rotating magnetic field and magnetic moment breaks down [22]. This is known as the critical frequency. At high fields or high frequencies (or both), the torque is controlled by the induced moment. At low fields or low frequencies, the torque is induced by the permanent moment. This complicates control of the magnetic nanoparticles as angular speeds would ideally be as high as possible to permit faster response time and possibly reduce sensor size. Higher speeds and higher fields result in a greater phase lag as the magnetic moment needs more time to come out of saturation [23].

Two field modes were considered, alternating magnetic fields and rotating magnetic fields. Alternating fields only generate one of two magnetic directions, like a stationary electro- magnet. When applying positive and negative currents, the magnetic field “flips”. Unlike rotating magnetic fields, which are more complicated to setup. The magnetic field rotates like a clock and can point in every direction within a plane. Each has a different dependence on phase lag. The rotating field has a much larger dependence than the alternating field does [15]. So it especially important not to spin
the nanoparticles too fast if the field magnitude is limited as proper rotation cannot be achieved. Studies have shown that rotational speeds up to 2 kilohertz are possible at field strengths of one millitesla without risking critical phase delays [14].

3.1.2 Gyroscopic Motion

There are three characteristics of interest of a gyroscope that one can use to derive angular position. These include torque, rotational inertia and precession. Torque is used to get an object spinning, while rotational inertia is required to keep external forces from changing the objects orientation. If an object that is spinning experiences a disturbance, whether it be friction, or gravity or other acceleration, precession results.

When a force is exerted tangentially on an object, that object will spin about its axis. The resulting torque ($\tau$) is cross product of the force and radius (see (3.5)) of the object and is shown in Figure 3.1.

$$\tau = r \times F$$ (3.5)
Torque also results in a change in angular momentum. So

\[ \tau = \frac{dL}{dt} \]  \hspace{1cm} (3.6)

where \( L \) is angular momentum. \( L \) is also a function of angular velocity and the moment of inertia, \( I \).

\[ L = I \omega. \]  \hspace{1cm} (3.7)

Taking the derivative results in a new equation for torque is given by:

\[ \tau = I \frac{d\omega}{dt} = I\alpha \]  \hspace{1cm} (3.8)

where \( \alpha \) is the angular acceleration. The moment of inertia for a sphere can be shown as:

\[ I = \frac{2m+4r^2}{5} \]  \hspace{1cm} (3.9)

In this equation, \( m \) is the mass and \( r \) is the radius of the sphere. Substituting \( I \) from (3.9) into (3.8) leads to an equation relating torque to angular acceleration, mass and diameter as shown in (3.10):
\[ \tau = \frac{2m + r^2 + \alpha}{5} \]  

(3.10)

This is the standard textbook equation for torque that applies to any spinning object. When dealing with Gyroscopes, there is the additional torque that is not applied to keep the sphere spinning, but instead to attempt to tilt the axis. This results in a motion of the rotational axis around the nominal alignment at an angular velocity \( \Omega \). This is different, and at a much lower speed than the rotational speed of the object itself, \( \omega \) as shown in Figure 3.2.

![Figure 3.2. Nanoparticle Precession](image)

The nanoparticle, when undisturbed, spins about the z axis. An external torque moves this spin axis toward either the x or y axis. Overall, momentum is preserved, but a second spin component is added. Torque can be derived as a differential angular momentum per small unit of time, so equation (3.6) and be rewritten as

\[ dL = \tau \, dt \]  

(3.11)
It can be shown that for small variations in the angle $\phi$ (d$\phi$) of Figure 3.2, small deviations result in inertia $dl$.

\[ dl = L d\phi \]  

(3.12)

Dividing (3.11) by (3.12) leads to

\[ \frac{dI}{dL} = \frac{\tau}{L} \frac{d\phi}{dt} \]  

(3.13)

From (3.7) it can be shown that

\[ \frac{dI}{dL} = \omega \]  

(3.14)

Substituting $dI/dL$ from (3.13) and the precession angular spin velocity $\Omega = d\phi/dt$, it can shown the torque, $\tau$, is approximately given in (3.15) as

\[ \tau = \Omega I \omega \]  

(3.15)

Equation (3.15) is an approximate representation precession torque $\tau$. This value is key to deriving angular information from a gyroscopic sensor with rotating nanoparticles. By measuring the energy to overcome this torque, the precession angle can be derived.

3.1.3 Theory Behind MEMS

MEMS does not refer specifically just to gyroscopic sensors. A more proper term is “Inertial MEMS”. They come in one, two, and up to six axis of simultaneous sensing in
one device. A good inertial sensor design should address bandwidth, drift, linearity, sensitivity, dynamic range, shock survivability and power consumption [20]. MEMS sensors are small in size and weight and consume relatively low power. There are many technologies used in MEMS sensors including piezoresistive, optical and most common, capacitive. In the capacitive design, two plates are usually setup in a comb configuration, to maximize the capacitance. One is fixed, while the other can flex due to external acceleration. This mass-spring relationship can be described by (3.16) [24].

\[ D = \frac{M}{k_{sp}} \]  

(3.16)

The amount of separation is labeled as “D”. M is the mass, and \( k_{sp} \) is the spring constant. Adding more mass to the moveable plate or decreasing the tension on the spring can make this device very sensitive to inertia. There are sometimes several “comb” configurations per device, each sensitive to a different level of motion. A change in charge on the capacitance is due to a change in capacitor configuration. This has been shown to be measureable by using (3.17) [60]:

\[ \Delta Q(x) = \frac{dc(x)}{dx}V\Delta x \]  

(3.17)

By measuring the capacitance \( C(x) \) with a bias voltage \( V \) and change in charge \( Q(x) \), the change in position \( \Delta x \) can be inferred. These measurements are dependent on Figure 3.3.
By changing the moment arm to the mass or the size of the mass itself, the sensitivity can be adjusted.

Like nanoparticle based gyroscopes, MEMS are micro machines. MEMS require a sensitive measurement of capacitance while the nanoparticle based gyroscope requires a sensitive means of measuring AC current. MEMS can be fabricated to handle multiple dimensions while the nanoparticle based gyroscope inherently handles two as presented in this dissertation. MEMS presently is much more accurate but there is no reason that a nanoparticle based gyroscope could not attain similar accuracy with more research and experimentation.

MEMS technology advances have slowed as the main focus of research is in trying to make the sensor simpler and easier to fabricate. Recent attempts at trying to merge a MEMS sensor into an Application Specific Integrated Chip (ASIC) failed because the heat from the ASIC distorted the comb structure, distorting the results as presented at the 2016 Inertial Conference. A nanoparticle based gyroscope, once advanced to be as small
as a typical ASIC, should not have these limitations. Heat does add to thermal agitation, increasing the torque resistance as indicated by equation (3.3). This term was ignored because of the scale of the sensor described in this dissertation, but can be compensated for. Nanoparticles in solution may accommodate a wider variety of shapes than MEMs, since it does take the form of a solution. An ASIC may someday be encased in a solution of magnetic nanoparticles, provided cooling and magnetic immunity as well as gyroscopic sensing.

3.1.4 Rotating a Magnetic Dipole

Rotating and controlling magnetic field is simple, but presents some challenges when dealing with magnetic nanoparticles. Rotating fields are used in many applications, but specifically in the design of multi-phase induction motors. The speed of these motors is dependent on the frequency of oscillation of the input current. Three phase motors are most common as they produce high torque while construction is simple. Less common are two phase motors but this concept is closer to the method proposed in this dissertation to rotate magnetic nanoparticles.

In a two phase induction motor design there are two main components, the stator and the rotor. The stator is the stationary component, providing most of the magnetic fields to rotate a rotor. To simplify this description, the rotor will be assumed to be a permanent two pole magnet. The stator is designed with poles or electromagnetics that, when energized, create a field to attract or repel the poles of the rotor. In this example,
the number of poles in the stator is equal to the number of phases of input current, or a multiple of the number of phases. In this case, the number of pole pairs is two. They are oriented at the same angle from each other as the phase angle between the phases, 90°. This is illustrated in Figure 3.4. The stator is shown twice, illustrating how each pair of poles is wired independently.

As the coils are energized with AC power, it can be shown that the generated magnetic fields will result in a rotor that will rotate continuously. This is illustrated in Figure . Each circle at the top represent the magnetization state of the stator based on how the four electromagnets are energized from Figure 3.4. Each set of coils attracts or repels the
motor “bar magnet” which is permanently polarized with north (red) and south (black) poles.

![Figure 3.5. Motor Pole Phase Stages](image)

One set of poles sets the position \( x \) of the rotor bar according to the equation

\[
x = \sin (wt) \quad \quad (3.18)
\]

where if \( x = 1 \), then the north pole points up and if \( x = -1 \), then the north pole points down. It is possible to operate this motor with only one set of poles but this presents some stability and startup issue problems. The other coil will attract each pole according the equation

\[
x = \sin (wt+\pi/2) \quad \quad (3.19)
\]

When used together, the bar magnet aligns to the vector sum of \( \sin (wt) \) and \( \sin (wt+\pi/2) \). If a lot of friction is present, or the mass of the rotor is large, then there must be sufficient torque to turn the rotor. The torque is provided by the energy in the magnetic
field of the windings. More windings will provide more magnetic field and more torque, provided that the core material in the stator doesn’t saturate.

Spinning magnetic nanoparticles presents similar challenges as spinning a rotor in an AC motor design. Both have an isolated rotor, although there are many thousand rotors in the nanoparticle sensor. The nanoparticles are only magnetized when exposed to a magnetic field, while the motor discussed here requires a permanent magnet. There are motors that do not require a permanent magnet, but they will not be discussed in this dissertation. A similar strategy used to rotate a motor is used to smoothly rotate the nanoparticles and provide enough torque to overcome viscosity of fluid in solution.
CHAPTER 4

COMBINING CONCEPTS WITH NANOPARTICLES

4.1 Theoretical Design

By combining the methods of rotating nanoparticles and generation of rotating magnetic fields a practical sensor has been derived that may be comparable to the inertial MEMS sensor in size and the early stages of performance. A sensory based application involving rotating magnetic nanoparticles depends on the signal obtained from disturbances in the nanoparticle rotation. Research has been conducted on the limitations of rotating a single nanoparticle as shown in Section 3.1.1.

A sensor based on one or even a few magnetic nanoparticles would not be desirable as the signal to noise ratio would be too low. Increasing the number of spinning nanoparticles amplifies any disturbance signal as long as the nanoparticle interaction is minimized. Figure illustrates a method to accomplish this [25]. To be an effective sensor, the number of wires should be maximized while keeping the volume to a minimum. The number of wires is limited by the gauge of the wires which is determined by the amount of current or magnetic field required. Each horizontal wire above and below the nanoparticles conducts current in phase. The perpendicular wires conduct current 90° out phase of the horizontal wires.
All of the nanoparticles can maintain their relative position and spin freely while minimizing the risk of overcrowding and collisions.

One impracticality of Figure is that there is no simple current return path for either phase. A hybrid method of rotating the magnetic nanoparticles is preferred that takes some of the advantages of the planar method of Figure with the Helmholtz method of Figure 2.4. This method would start with two independent coils. Each coil is wound perpendicular to the opposing coil as shown in Figure 4.2.

This configuration produces a relative uniform field inside the coils as well as maintaining the perpendicular fields of the planar configuration to eliminate the chance of rotation glitches when the nanoparticles align with the coil field extremes.
Ideally, if the wires would form infinite round solenoids, the magnetic field inside the coils would be totally uniform [26]. This, of course, is not possible. Not only is the sensor limited in length, but attempting to make the windings round wound make the sensor spherical resulting in a wire orientation that is no longer perpendicular in one plane but in two planes.

Although it can be shown that inside the sensor, the field rotates at the same speed, there are distortions near the sides of the body of the sensor. Using MATLAB/SIMULINK® and the Biot-Savart law, the field variation can be estimated as shown in Figure 4.3 for one instant in time at a constant height throughout the sensor. An ideal sensor would have a flat response across the entire surface. This variation will be accepted as a limitation of this sensor and can be minimized with a flatter, wider sensor and with more windings.

![Figure 4.3. Magnetic Field Variation for a Square Sensor at a Constant Height](image.png)
A second simulation was produced using CST® software which is meant for modeling near and far electromagnetic fields. The purpose of this simulation is to show the range and direction of magnetic fields external to the sensor. A snapshot of the simulation is shown in Figure 4. Note that the color indicates the intensity of the magnetic field. Red to yellow correlates to higher intensity, while blue is the lowest. The highest intensities are not shown, but are located, as preferred, inside the enclosure. Calculated magnetic fields inside the sensor averaged around 0.002 Tesla. As a comparison, the Earth’s magnetic field measures about 0.5 Gauss at the surface. One Tesla is the equivalent to 10,000 Gauss so these sensors are generating about 40 times the field strength as the Earth.

![Figure 4.4. Radiated Magnetic Signature](image)

There are biological sensory applications where the magnetic moments of free floating and captive nanoparticles can be distinguished based on phase measurements [15]. This dissertation focuses on a similar approach where a change in orientation can be
measured when magnetic nanoparticles are exposed to a rotating magnetic field. Therefore, it will be necessary to quantify the dynamic effects of any disturbance to the normal moment rotation caused by the rotating fields.

As the magnetic rotational frequency is increased, the hydrodynamic frictional force overcomes the magnetic torque [1]. This is one cause of the phase delay between the nanoparticle orientation and the magnetic field orientation. As mentioned earlier in this dissertation, these delays can result in rotational breakdown, corrupting any sensory application reliant on the rotation. Thermal agitation is another source of phase delay [21]. The breakdown frequency is dependent on magnetic field intensity. Magnetic field magnitude and frequencies are chosen as to keep the phase lag below a 90 degrees. This magnetic field strength can vary from 5 mT to 10 mT [22]. This has been shown to fall at frequencies between 100 Hz and 2000 Hz, with higher frequencies requiring a higher magnetic field strength.

4.2 Theory of Operation

By examining a single nanoparticle, it is easier to see how this type of sensor can be used to detect angular acceleration. Like a simple gyroscope, each nanoparticle spins on its axis in its confined area. Any “wobble” of its axis due to precession will be negated. The magnetic field is the gimbal, keeping the axis of the nanoparticle locked fixed unless disturbed by an external force. The nature of the AC currents in Figure 2.9 keeps the nanoparticles from drifting together toward the wires or magnetic sources. The
nanoparticles align their magnetic moment axis with the magnetic field direction, which is constantly rotating.

Should the system experience an angular shift, like a banking of an airplane, the moment axis of the nanoparticles would also shift. This shift results in precession as discussed in Section 3.1.2. Equation (3.15) identified the torque needed to produce precessed rotation at speed \( \Omega \) while spinning on its axis at speed \( \omega \). This precession rotation must be overcome by the rotating magnetic field by realigning the nanoparticle magnetic axis with the rotating magnetic axis. This will be seen as a change in current to the sensor since the magnetic field is directly proportional to current. When the external force is removed (angular acceleration ends), the precession ends and the current should return to the steady state of an undisturbed sensor. The greater the disturbance to the rotation will result in a greater effect on the input current. Each nanoparticle contributes its own resistance to the change in orientation. The more nanoparticles contained in the solution, the more energy is needed to realign all the nanoparticles as long as nanoparticle to nanoparticle interaction is minimized.

Torque introduced by an external force is overcome by the same magnetic force that keeps the nanoparticles spinning. The only difference is that the spin axis of the nanoparticle has been moved and must be realigned to the stable position before the disturbance as shown in Figure 4.5. The torque resulting from an imposed magnetic field can be determined as indicated in equation 3.4. As an approximation, the last portion of
the equation representing temperature affects is removed as this is negligible compared to the magnetic forces and frictional drag resulting in (4.1)

\[ \tau = M \times B - 6\eta V \omega \]  

(4.1)

where B is the imposed magnetic field and M is the magnetic moment [12]. The angle \( \theta \) is the difference between the magnetic flux direction and the orientation of the magnetic moment. If these were aligned, the torque would be zero. Maximum torque exists when this angle is at 90°. This cross product can be rewritten as (4.2).

\[ \tau = l\alpha - 6\eta V \omega \]  

(4.2)

Equation (4.2) describes the torque induced on a nanoparticle spinning at angular acceleration \( \alpha \) by an external B-field without precession. The nanoparticle is assumed to be spinning on its axis and the axis is stationary, that is, not “wobbling”. It is important that the viscous portion of (4.2) \((-6\eta V \omega)\) does not create enough drag to increase the phase shift between the magnetic field and the nanoparticle moment more than 90°. This is controlled by the speed, \( \omega \). Most of the torque is involved in spinning up the nanoparticles. In a frictionless environment, there would be almost no torque, and thus
only enough current would be needed to overcome friction and keep the nanoparticles spinning. The magnetic moment and field would be practically aligned all the time.

\[ \text{Figure 4.5. Disturbed Nanoparticle in an Alternating B Field} \]

A similar phenomenon occurs if the nanoparticles are all forced to random orientations. Only the component of the field in line with the moment would continue to keep it spinning. Depending on the angle, this could drop the torque below the friction torque, resulting in a quick reduction in speed. The remaining magnetic torque would be focused on realigning the nanoparticle with the field. Once this happens, the nanoparticles begin to gain rotational inertia again, which should be evident as an increase in input current.

Similar to (4.2) is the state of a spinning nanoparticle when an external force induces a secondary motion of the primary magnetic moment axis, so that the axis is no longer in line with the magnetic flux. This is similar to a spinning top that is not perfectly balanced. At some point, gravity takes advantage of the imperfections and attempts to "wobble" the main axis until the top falls over. The same effect is hypothesized about the
spinning nanoparticles. When a system of spinning nanoparticles is interrupted, moved, or rotated, the axis of each nanoparticle is moved so that it is no longer aligned with the magnetic field. The resulting precession is modified from (3.12) to include the fictional drag in (4.3).

\[
\tau = \Omega I \omega - 6\eta V \omega \quad (4.3)
\]

This equation describes the torque induced on a nanoparticle spinning at angular frequency \( \omega \) while precessing around the imaginary axis at a frequency of \( \Omega \) due to a disturbance. Note it is assumed that \( \Omega \) is much less than \( \omega \).

In both cases of (4.2) and (4.3), the torque is induced by an external magnetic field. This magnetic field cannot be aligned with the magnetic moment, but out of phase with it by some angle \( \theta \). But \( \theta \) cannot be the same in both cases. They are referenced as \( \theta_1 \) and \( \theta_2 \). When there is no precession, \( \theta_1 \) is the difference between the magnetic moment and the magnetic field as the magnetic moment lags behind the magnetic field. In the case of precession, not only is there a lag, but there is a shift off axis. Figure illustrates this extra angle. So the difference in phase between the magnetic moment and the magnetic flux is the vector sum of the angle between magnetic moment and the magnetic field, and shift of the axis of rotation or \( \theta_2 \). The torque to create this condition is shown in equations 4.4 whereas the torque to spin an undisturbed nanoparticle is shown in equation 4.5.

\[
\tau = \Omega I \omega - 6\eta V \omega = MB \sin \theta_1 \quad \text{(precessed)} \quad (4.4)
\]
\[ \tau = I_\alpha - 6\eta V\omega = MB\sin \theta_2 \quad \text{(not precessed)} \quad (4.5) \]

(4.4) and (4.5) can be rewritten to solve for B, which is proportional to current as given by (4.6) and (4.7):

\[ B = (I\omega - 6\eta V\omega) / M(sin \theta_1) \quad \text{(precessed)} \quad (4.6) \]

\[ B = (I_\alpha - 6\eta V\omega) / M(sin \theta_2) \quad \text{(not precessed)} \quad (4.7) \]

Equation 19 shows a direct dependence on the inertia of the nanoparticles and the speed with which they are rotating and an indirect dependence on the moment. This change in magnetic field applies to each individual magnetic nanoparticle. These equations can be further expanded by assuming each nanoparticle is roughly spherical. The moment of inertia is estimated as \( \frac{2}{5} mr^2 \). The final equations describing precessed and normal spinning motion are given in (4.8) and (4.9).

\[ B = (2mr^2\omega / 5 - 6\eta V\omega) / M(sin \theta_1) \quad \text{(precessed)} \quad (4.8) \]

\[ B = (2mr^2\alpha / 5 - 6\eta V\omega) / M(sin \theta_2) \quad \text{(not precessed)} \quad (4.9) \]

Each differential component of the wires in the sensor contributes to the magnetic flux for each nanoparticle. These individual contributions can be summed according to the Biot-Savart law to estimate the combined effect of the disturbance on the input current. Of the quantities shown in (4.8) and (4.9), mass “m” and radius “r” are known or are easily determined from a manufacturer’s data sheet for magnetic nanoparticles.
The magnetic moment can be found from the results of ref [19]. In this study, nanoparticles were subjected to different pressures and varying levels of magnetic fields, both direct and varying. Magnetic moments were determined for both multiphase and single phase nanoparticles. This article only focuses on single phase nanoparticles of magnetite (Fe₃O₄), similarly to what was used in the study. Based on the results, M can be assumed for magnetite at levels of alternating magnetic field between 5 and 10 mT to be approximately \(0.025 \times 10^{-6} \text{Am}^2\). The measured value of magnetic field, which can be derived by measuring the induced currents.

### 4.3 Expected Results

As shown in Section 4.2, any change in orientation, direction or linear motion will upset the natural rotation of the magnetic nanoparticles, leading to some precession. When the nanoparticles are closely aligned with magnetic field, torque is at a relative minimum. The nanoparticles will absorb enough energy to overcome friction. This should be an equilibrium sometime after startup. When the nanoparticles are experiencing precession, the spin is no longer controlled by the magnetic field because the nanoparticle axis is no longer aligned. The energy needed to keep the spin rotating is not needed, and an expected drop in current is expected. After the nanoparticles begin to rebound and realign with the magnetic field, an increase in current is then expected, back to the equilibrium state. An unintended consequence of this prediction is that the direction of
rotation is indistinguishable. Clockwise rotation cannot be distinguished from
counterclockwise rotation. The orientations as shown in Figure can be distinguished from
each other by comparing the change in currents during a disturbance.

![Orientation A and Orientation B](image)

*Figure 4.6. Sensor Rotation*

Each coil contributes half the energy to the magnetic rotation. If the sensor is rotated
as shown on orientation A, one coil simply “rolls” while the other is flipped on end by 90°.
The nanoparticle should not significantly be affected by the orientation in line with the
coil that rolled. The nanoparticle would experience a significant shift when flipped 90°.
This should be visible when rotating the sensor on different axes. The expected order of
operation is as follows:

1) Sensor is up and running, nanoparticles are spinning in equilibrium
2) A disturbance changes the orientation of the sensor
3) The nanoparticles respond by attempting to maintain their previous spinning
   orientation, which is now shifted from the magnetic field direction
4) A drop in input current results due to the loss of nanoparticle spin torque due to the magnetic field axis misalignment (4.6) 

5) Current is regained as the nanoparticles realign to the new magnetic field direction, requiring a new startup torque until equilibrium is regained. (4.7) 

In order for there to be rotation, the torque imposed by the magnetic field must overcome the torque produced by the fluid resistance as shown in equation (3.4). Table 4.1 shows that the concentration is much higher for the water based sensor than the toluene based sensor. Higher concentrations are preferred, although lower viscosities are also preferred. Lower viscosities increases the probability of a true precession during a disturbance instead of just a re-alignment.

Because the second term of equation (3.4) is high relative to the first term, the shape of figure 4.7 is expected. The blue trace identifies the orientation and rate of orientation change. The farther from horizontal, the greater the effect of viscosity, resulting in a longer recovery time. This is estimated to be proportional to the worst case of a 90° shift at the same rate. Point “A’ in Figure 4.7 indicates a 2/9 magnitude affect while point B indicates a 1/2 magnitude change relative to a 90° change.

If precession does result, then the impact is less as the nanoparticles would continue to spin, and only the precession torque would have to be overcome. Chapter 5 will show that precession is indicated when less than 180° are introduced. The torque level between two spikes is maintained.
A plot of the expected results is shown Figure 4.9. The plot is normalized so the current magnitude is relative to a maximum delta drop of “one” which can vary from 2 mA to 10 mA depending on the sensor and conditions. Each current change follows closely with the angle change until the rotation stops, at which point the nanoparticles can again
realign to the rotating magnetic field and resume normal rotation. This is indicated by a rising current back to steady state, represented by a delta of zero current. Figure 4.10 shows predicted results when varying the angle from 20° to 90°.

**Figure 4.9.** Predicted Response to 180° Motion

**Figure 4.10.** Predicted Response to Varying Motion
For a rough approximation, the B field can be estimated as in a solenoid of length L using μ as the relative permeability and N as the number of turns as in (4.1).

\[ B \sim \mu NI_c/L \] (4.1)

In (4.1) \( I_c \) is used instead of I for “current” to distinguish it from “Inertia”. Therefore, measured current is directly proportional to the generated magnetic field. The change in current would be inversely proportional to the sine of the angle of disturbance if the disturbance would result in a loss of spin. If the disturbance results in spin being maintained, it may be possible to maintain the reduced spin with reduced current, assuming that the axis cannot be realigned due to a constant external force such as gravity. This would account for the stabilized state in between angle transitions.

The frictional losses reducing the imposed torque due to the viscosity of the fluid can be estimated using the values of Table 5.1 and formula of (3.2). Table Error! Reference source not found. 4.1 contains all the derived and inherent values used in (3.2).

\textit{Table 4.1. Water and Toluene Properties}

<table>
<thead>
<tr>
<th></th>
<th>Water solution</th>
<th>Toluene solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanoparticle Mass m</td>
<td>( 7.065 \times 10^{-17} ) g</td>
<td>( 2.09 \times 10^{-17} ) g</td>
</tr>
<tr>
<td>Nanoparticle Radius r</td>
<td>( 15 \times 10^{-7} ) cm</td>
<td>( 10 \times 10^{-7} ) cm</td>
</tr>
<tr>
<td>Nanoparticle Volume V</td>
<td>( 1.413 \times 10^{-17} ) cm(^3)</td>
<td>( 4.189 \times 10^{-18} ) cm(^3)</td>
</tr>
<tr>
<td>Fluid Viscosity ( \eta )</td>
<td>1.002 cp</td>
<td>.590 cp</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>500 hz – 1500 hz</td>
<td>500 hz – 1500 hz</td>
</tr>
<tr>
<td>Concentration</td>
<td>5mg/ml</td>
<td>20% wt</td>
</tr>
<tr>
<td>Nanoparticles in sensor</td>
<td>( 1.42 \times 10^{16} )</td>
<td>( 7.18 \times 10^{14} )</td>
</tr>
</tbody>
</table>
Based on these values, the amount of Torque needed to overcome friction is calculated in Table 4.2. The amount of torque friction to overcome is 5.7 times greater in water than in toluene. The water solution had a higher viscosity and slightly larger nanoparticles and a higher density. These are all important factors when creating a nanoparticle based sensor.

<table>
<thead>
<tr>
<th></th>
<th>Water Solution (@ 1500 Hz)</th>
<th>Toluene solution (@ 1500 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6\eta V\omega$</td>
<td>$8.00 \times 10^{-13}$ cp(cm$^3$) rad/sec</td>
<td>$1.40 \times 10^{-13}$ cp(cm$^3$) rad/sec</td>
</tr>
</tbody>
</table>

When referring to the viscosity of either water or Toluene the dynamic or absolute viscosity is assumed. A higher viscosity means a thicker, slower moving liquid that would present more “shearing” stress against an object in its path. This shearing stress creates more friction. More friction means more force, or torque is needed to rotate the nanoparticles. Lower viscosity is normally preferred as friction represents losses. An ideal sensor would contain free floating nanoparticles in a vacuum with no friction to oppose their motion. This setup would result in more of a true precession during a disturbance, instead of a spin-down as the water based sensor experienced. The downfall of a vacuum based system is that there is no simple way to keep the nanoparticles suspended when not powered as Brownian motion does because of the nanoparticle size.
The nanoparticles would be more likely to be attracted to each other if no resistance were in their path when magnetized. A larger, single nanoparticle based gyroscope would be more practical in a very low viscosity environment.

Larger nanoparticles present a similar issue as higher viscosity. Larger nanoparticles have more surface area and are more susceptible to surface friction when spinning. When included in solution with a low viscosity fluid, the inertia of the nanoparticle helps to create precession when the system is disturbed as the spin does not stop as quickly. The experiments performed in this dissertation expected more precessed behavior, but because of how quickly the nanoparticles lost spin when shifted off-axis, most inertial information came from how much spin was lost and the amount of time to get the nanoparticles up to equilibrium.

Higher densities contribute to more accurate sensors regardless of the viscosity or nanoparticle size. There is a limit as too many sensors per unit volume increases nanoparticle interaction, inhibiting spin and precession with more collisions. Each nanoparticle contributes its own affect due to disturbances to the system. All nanoparticles do not react exactly the same at the same time, especially when the magnetic field is not perfectly uniform, but the average of tens of thousands of nanoparticles should produce a consistent signal.
CHAPTER 5

TEST RESULTS

5.1 Test Setup

There are infinitely many ways to test an inertial sensor. The sensor can be rotated, linearly accelerated, exposed to shock, or any number of other ways to exert a force resulting in a linear or angular acceleration. The tests proposed in this dissertation are kept simple to prove the concept under minimal resources. It is the intention that the results presented here could be further refined with improved test equipment and methods to continue to advance the technology.

Many different tests were performed on a variety of different magnetic nanoparticle based sensors. Only the most reliable and successful tests are documented. One test that was fairly easy to perform, produced a large amount of information. The test was the simple rotation of the sensor over several predefined angles, starting with a stationary, level sensor. This is shown in Figure 5.1. The sensor orientation is controlled via a stepper motor and rotated through various degrees of motion, held in place for a few seconds, and returned to the “home” level position before moving to the next angle.

Both rotations around the “X” and “Y” are tested independently, because there was only one high precision current sensor available. Rotation in both axes validates the
claim that it is possible to determine inertia in 2 dimensions using only one sensor. The test setup is illustrated in Figure.

A signal generator is shown at the top left of Figure 5.1. This provides the key AC signal at the various frequencies used during the tests. The output of this instrument is buffered with a dual audio amplifier. This provides isolation between the two coils in the sensor and allows independent adjustment so that the current into the coils at the beginning of a test is approximately the same. Two AC current sensors are used to passively monitor the current into both coils. An oscilloscope with two hall-effect current probes is used to verify that the currents in both coils of the sensor are out of phase by 90°. The 90° phase
The angle between the currents is very crucial in order to make sure the magnetic fields are rotating properly. The currents are set at 90° out of phase with respect to each other with the addition of an extra series capacitance in one of the circuits. This capacitance value had to be re-evaluated at each test as the magnetic nanoparticle coil setup impedance changed with frequency.

Next the mechanical drive portion of Figure 5.1 is described. Two Arduino microcontroller circuits are implemented. One to provide stepper motor control, and the other to capture real time data from the precision current sensor. This controller is setup with an external analog-to-digital converter to allow up to 16 bits resolution or about 0.0762 mV over a 5V range. Only 14 bits are needed for a resolution of about 0.3051 mV over a 5V range. A fairly standard 9V 800 step full-circle stepper motor is used, which allows approximately just over 0.45° per step (2.22 steps per degree). The two Uno Arduino controllers are synchronized via interrupts to correlate movement with current measurement.

A critical component of this setup is the current sensor. The sensor current must be measured to be less than 0.5 mA change in current but also support a typical continuous current of 250 mA. The sensor produce a true-RMS output with a response time of 250 msec. The measureable frequency range is from 20 Hz to 5 KHz, so these parts are well suited for the operating frequency range of these experiments. The RMS measurement limitations do restrict the results as will be explained later in this section. A custom design may be necessary to derive a more accurate method of measuring the
change in current. This is important for the design of a smaller size and more dynamic sensor. For the purposes of this dissertation, the concept has been validated, but at the limits of the measurement technique.

Two different motion profiles were chosen to test the response of the sensors. Each profile includes multiple rotations, each at reduced angular speeds to test both the response and lag of each sensor. The first profile was chosen to start and end each motion in a “stable” state. This would test the sensors ability to respond to a continuous change and whether two different stable points (180° out of phase) will result in similar current drawn.

The second profile was chosen to test when one position is a stable (horizontal position), but the other is an unstable, (non-horizontal position between 0° and 90°). The two profiles are shown in Figure 5.2.
5.2 Magnetic Nanoparticle Specifications

Two varieties of magnetic nanoparticles were used for this experiment. Both were readily available from Sigma-Aldrich. The significant differences between the samples included the type of fluid used for the solution and therefore the viscosity of the fluid, and the size of the nanoparticles. One sample was toluene-based and the other was water-based. Both samples contain magnetite (Fe₃O₄) nanoparticles. The water based sample contains nanoparticles that are about 33% larger on average than the toluene based sample. This significant factor will be explained in the findings section of this chapter. The characteristics of each sample is shown in
Table 5.1. Solution Properties

<table>
<thead>
<tr>
<th>Sample</th>
<th>Solution</th>
<th>Average nanoparticle size</th>
<th>Density</th>
<th>Sigma Aldrich Part number</th>
<th>Dynamic Viscosity at 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water</td>
<td>&lt;30 nm average size &lt;100 nm</td>
<td>1.17 g/mL±0.1 g/mL at 25 °C</td>
<td>720704-100G</td>
<td>1.002 cP</td>
</tr>
<tr>
<td>2</td>
<td>Toluene</td>
<td>20 nm average size (18-22 nm)</td>
<td>.865 g/mL at 25°C</td>
<td>700304-5ML</td>
<td>0.590 cP</td>
</tr>
</tbody>
</table>

5.3 Control Results

Before conducting any experiments on real test samples, the experimental setup was checked for electromagnetic noise, vibrations, and clearance to try to eliminate any false data that could corrupt the results. This was done using a sample composed of only tap-water. No nanoparticles were added, although there are traces of minerals in tap-water, these were viewed to be insignificant compared with the concentrations in the real samples.

Two different winding configurations were tried. One with 50 windings per coil, and one with 100 windings per coil. An initial attempt was made at measuring a sensor with only 10 windings with no success. One hundred windings appeared to overdrive the sensors. The magnetic field was too strong and immediately recovered any disturbance, reducing any useful orientation information. Fifty windings seemed to be the minimal number of windings to give a credible output at the size of sensor tested. Both sensors
were constructed the same size and with the same number of windings. Because Toluene is fairly corrosive, plastic could not be used to contain the solution. Two glass vials were used and taped together to form a square base. Both coils need to be the same size so the resulting magnetic field distortions can be minimized. One disadvantage of this method is that it increases the surface area contact with the nanoparticles. This was an acceptable risk because the glass vials were the only alternative without creating a custom container. The resulting control sensor and one of the sample glass vials is shown in Figure 5.3.

![Image](image.png)

*Figure 5.3. Sample Construction*

The control was run through a series of rotations. Starting horizontally at rest, the control was rotated 20° and back to horizontal, 45° and back to horizontal, 70° and back to horizontal, and finally, 90° and back to horizontal. At each state, the sensor was held for 0.5 second before proceeding in order to allow time for stabilization. The process is automatically repeated four times. The first iteration has the fastest transition times.
allowed by the motor. Each iteration after that has slower transition times than the previous iteration. This process checks the sensor for angle accuracy and response time. Figure 5.4 – 5.7 show the rotation angle in blue, and output results of one coil when rotated either on the x-axis (orange) or y-axis (grey) as indicated.

Figure 5.4. Control Data at 500 Hz

Figure 5.5. Control Data at 750 Hz
Figure 5.6. Control Data at 1000 Hz

Figure 5.7. Control Data at 1500 Hz

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Except for an occasional current spike, the responses are all at or below 0.6 mA, the lowest specified limit for the current sensors. Higher operating frequencies result in higher noise transients. This has been determined to be partially due to noise transmitted by the Audio amplifier. Efforts have been made to reduce this noise such as twisting output wires and covering the amplifier with a stainless metal enclosure. The current in the two coils were verified to be out of phase with one another for each frequency. The phase difference is shown at 500 Hz in Figure 5.8.

The grey traces in Figures 5.4 – 5.7 represent the orientation where the coil being monitored is experiencing the greatest change or “end-over-end” orientation. In the other orientation, the coil is experiencing a basic “roll”. This
explains why the orange traces are lower in magnitude for each operating frequency. The same effect will be evident for an actual nanoparticle based sensor will be shown later in this chapter.

5.4 Sensor Saturation

When performing these experiments, it is important to know if the sensors themselves are saturating, where the sensor behaves as a short circuit. Driving a short circuit can hide the changes in current when orientation changes occur. Magnetite can take time to recover and this time is increased that farther into saturation it is driven. More recovery time means more delay and can result in rotation reversal. The precision current sensor can measure between 0.0 and 0.5 Amps, with a midpoint measurement point of 0.25 amps. This is the most linear and accurate point of the measurement curve and the preferred mode of operation, as long as it is sufficiently far from saturation. Both water and toluene sensors were tested at each operating frequency for AC saturation. The results are shown in Figures 5.9 and 5.10.
Both the water based and toluene based sensors react similarly because the saturation point is a function of anything in the core that is susceptible to magnetic fields. In both
cases, the material is the same, magnetite. The preferred area of operation around 2.5V is also not close to the saturation region, which is around 4.0V.

5.5 H$_2$O Solution Results

This first set of H$_2$O results was performed while rotating the sensor 180° first clockwise, then counterclockwise after waiting for three seconds. The transition time was increased with each iteration for a total of four iterations. Both orientations of Figure were tested and recorded on each graph. Figure 5.11 - Figure 5.14 came close to theoretical results. Each transition to 180° (clockwise) and back again to 0° (counterclockwise) produce a similar spike in current. This is shown in the green traces. The brown trace has a dramatically reduced response which is also predicted while the coil did not experience the orientation change, only a “rolling” affect. The magnitude of the current spikes should be fairly consistent because this is a function of the angle change. The spike width also follows fairly well with the time of the angle transition.

The first plots follow closely with the predicted plots of Figure . Each transition results in approximately the same drop in current. Clockwise or counterclockwise rotation did not change the response direction. Finally, slower rotations resulted in slower transitions. An interesting observation from the data occurred in Figure and Figure 5.14. As the rotational frequency was increased to over 1000 Hz, the drop in current decreased. This suggests that the sensor was able to recover from the
disturbance quicker. This may also be an artifact of better response to the jitter in the rotation due to the stepper motor movement.

**Figure 5.11.** H₂O 500 Hz 180° Rotation

**Figure 5.12.** H₂O 750 Hz 180° Rotation
Figure 5.13. H$_2$O 1000 Hz 180° Rotation

Figure 5.14. H$_2$O 1500 Hz 180° Rotation
Further testing has shown some unpredicted behavior. In the following graphs, the sensor was rotated at 20°, 45°, 70° and finally 90°. This process was repeated again four times with slower transition times induced for each subsequent cycle. In this experiment, orientation B rotations resulted in some steady state values after the transitions. These results were repeated for the 70° and 90° transition, but little to no effect was seen on the 20° or 45° transitions suggesting a minimum current was necessary to produce this effect. This may be an artifact of the measurement method and not the nanoparticle sensor. The overall current changes for these tests is almost an order of magnitude greater than the previous tests. Orientation A and B rotations still produce a predictable difference in output with orientation A output changes less than half that as measured with orientation B.

Figure 5.15 has an expected output similar to the control where the output is relatively unaffected.

Figure 5.15. H₂O 500 Hz <Orientation A>
Figure 5.16 shows some repeatable but unexpected output. The shape of the response directly corresponds to the induced rotation and magnitude of rotation.

**Figure 5.16.** H$_2$O 500 Hz <Orientation B>

**Figure 5.17.** H$_2$O 750 Hz <Orientation A>
Figure 5.18 and Figure 5.19 results are similar to the results at 500 Hz. The sensor at these rotational frequencies seem to only be sensitive to 70° and 90°.

For angles less than 45°, no signal was detected. The magnetic nanoparticles disturbance isn’t great enough when disturbed less than 45° to shift off axis and reduce its spin rate thus reducing the current required to maintain a spin. Note that the scale is reduced so that minor variations similar to the control plot aren’t noticeable.

![Graph: H2O And Fe₃O₄ at 750 Hz <Orientation B>](image)

*Figure 5.18. H2O 750 Hz <Orientation B>*

Again, similar results at 1000 Hz as shown in Figure 5.19.
The initial spike at approximately two seconds in figure 5.20 was due to the initial turn on of the stepper motor to begin the test. The motor steps were usually begun before the data acquisition was started. Similar to the Figure, some signal is observed 20° and 45°. It is theorized that this is a residual effect from the last transition to 90° as that sequence had the fastest rise/fall times resulting in longer recovery. See Figure 5.20 and Figure 5.21.
At 1500 Hz, a result similar to the previous tests at 180° reappears. The reaction magnitude decreased in Figure 5.22, suggesting an increase in reaction speed or a decrease in sensitivity.
Figure 5.22. H2O 1500 Hz <Orientation B>
5.6 **Toluene Solution Results**

The results obtained with the solution containing toluene are compared to the solution with water. As shown in Figure, both orientations reacted similar indicating a lack of effect of the rotation at the frequencies tested. The signal levels were close to the control levels.

*Figure 5.23. Toluene 500 Hz  180° Rotation*
**Figure 5.24.** Toluene 750 Hz 180° Rotation

**Figure 5.25.** Toluene 1000 Hz 180° Rotation
Even at varying degrees of rotation, the signal was still almost an order of magnitude less than the signal produced using water. A similar phenomenon to the water solution was observed in that during each rotation, the resulting signal was held until the nanoparticle sensor was rotated back to horizontal. Figure 5.27 is plotted to the same scale as the same plots generated for the water solution. Figure 5.28 is zoomed in to
show that although reduced, there is some correlation between angle and current. These figures are repeated at 750, 1000, and 1500 Hz. The results are shown in Figure.

![Figure 5.27. Toluene 500 Hz <Orientation A>](image1)

![Figure 5.28. Vertically Zoomed in Version of Figure 5.27](image2)
Figure 5.29. Toluene 750 Hz <Orientation A>

Figure 5.30. Vertically Zoomed in Version of Figure 5.29
Figure 5.31. Toluene 1000 Hz <Orientation A>

Figure 5.32. Vertically Zoomed in Version of Figure 5.31
Figure 5.33. Toluene 1500 Hz <Orientation A>

At 1500 Hz, the response comes closer to the predicted in Figure 5.34 where there is less effect of storing the signal and more of an indication of the magnitude of the rotation.

Figure 5.34. Vertically Zoomed in Version of Figure 5.33
The next several plots (Figure - 5.41) again show the effects on the current of the non-affected coil during a rotation at different degrees. Again both a relative scale and a zoomed scale is shown showing very little pattern to correlate to motion as predicted.

![Figure 5.35. Toluene 500 Hz <Orientation B>](image1)

![Figure 5.36. Vertically Zoomed in Version of Figure 5.35](image2)
Figure 5.37. Toluene 750 Hz <Orientation B>

Figure 5.38. Vertically Zoomed in Version of Figure 5.37
Figure 5.39. Toluene 1000 Hz \(<\text{Orientation B}\>\)

Figure 5.40. Vertically Zoomed in Version of Figure 5.39
Figure 5.41. Toluene 1500 Hz <Orientation B>

Figure 5.42. Vertically Zoomed in Version of Figure 5.41
5.7 Toluene at Higher Frequencies

Because of the reduced response at the frequency range of 500 Hz to 1500 Hz, higher frequencies were tested as the lower viscosity may be the cause of the limited signal. Increasing the speed should increase the resistance, possibly resulting in the disturbance torque contributing a larger component of the overall torque. This was shown not to be the case in Figure.

Figure 5.43. Toluene 2000 Hz
Figure 5.44. Toluene 2500 Hz

Figure 5.45. Toluene 3000 Hz
A summary of all the results of the various tests is shown in table 4.2. It indicates that the solution containing water had the best overall results. Rotations to 180° were most consistent. Rotation to angles less than 180° produced results above 70° to within 5° of accuracy. Most of this is due to the test equipment limitations. One can conclude that a change in direction can be inferred from the influence on the supplied current. Improving the accuracy, strengthening the signal and reducing the noise are challenges that still need to be solved. Further investigations are needed to examine the sensor with the toluene solution in order to obtain better results. It appears that the overall higher viscosity and relatively higher nanoparticle volume will be critical to achieving further success with this experiment.
Table 5.2. Experimental Results

<table>
<thead>
<tr>
<th>Figure</th>
<th>Orientation</th>
<th>Solution</th>
<th>Rotation frequency</th>
<th>Rotation Angle</th>
<th>Meets model</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.11</td>
<td>A+B</td>
<td>H₂O</td>
<td>500</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>5.12</td>
<td>A+B</td>
<td>H₂O</td>
<td>750</td>
<td></td>
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</tr>
<tr>
<td>5.13</td>
<td>A+B</td>
<td>H₂O</td>
<td>100</td>
<td></td>
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</tr>
<tr>
<td>5.14</td>
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<td>H₂O</td>
<td>1500</td>
<td></td>
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<tr>
<td>5.15</td>
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<td>H₂O</td>
<td>50</td>
<td>X X X X X</td>
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<td>H₂O</td>
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</tr>
<tr>
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<td>750</td>
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<td>5.18</td>
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<tr>
<td>5.19</td>
<td>A</td>
<td>H₂O</td>
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<td>70°,90°</td>
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<td>5.20</td>
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<td>Toluene</td>
<td>500</td>
<td>X X X X X</td>
<td>reduced 45°,70°,90°</td>
</tr>
<tr>
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<td>Toluene</td>
<td>750</td>
<td>X X X X</td>
<td>reduced 45°,70°,90°</td>
</tr>
<tr>
<td>5.31</td>
<td>A</td>
<td>Toluene</td>
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<td>X X X X</td>
<td>reduced 45°,70°,90°</td>
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<tr>
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<td>X X X X</td>
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CHAPTER 6

SUMMARY, CONTRIBUTIONS AND FUTURE WORK

6.1 Summary

Inertial sensors have continuously been improved and there is increased demand for these types of sensors. Nanoparticles have gained popularity in medical research since the early 2000’s. There are applications in the medical industry using and their application in sensors looks promising. Spinning nanoparticles to derive inertial properties may overcome some limitations of MEMS sensors. They appear to be scalable using smaller nanoparticles with certain liquid viscosities and rotational speeds. This dissertation may be the first application of using spinning nanoparticles in an inertial sensor.

Theoretical results show that relatively high rotating magnetic fields can be created with specific phase control of currents under 0.25 Amps. Almost 0.01 Tesla of flux density can be generated to direct magnetic nanoparticles trapped in solution. Experiments have validated most of the theoretical claims. Angles from 70° to 180° were detectable but with no better than 5° accuracy. Noise was a problem as the sensors made good antennas and better measurements were needed that rode on top of relatively high current signals. Test equipment limitations kept the signal accuracy down
to less than 5°, but further refinement of measurement techniques and current control should allow accuracies similar to today’s MEMS.

6.2 Contributions

This dissertation has presented an initial development of an inertial sensor using rotating magnetic nanoparticles in a solution. The contributions of this dissertation include:

1) A working initial prototype capable of measuring up to 180° of rotation.
2) A patent has been filed with the Western Michigan University to secure the rights of the design for future work
3) Limitations of the present method and design have been identified including lack of ability to identify direction of angular change, nanoparticle size, solution viscosity and concentration.

6.3 Future Work

This dissertation just began the investigation into the possibilities of a magnetic nanoparticle based gyroscope. Only two solutions have been tested. Many variables need to be investigated in order to shrink this sensor down to the size comparable to MEMS. These include:

1) Optimizing the solution concentration
2) Investigating other liquids beyond water and toluene

3) Refining the current measurement and reduction of noise susceptibility and emissions

4) Investigating the use of other magnetic nanoparticles besides magnetite.

5) Simplifying the drive signal with square wave signals instead of sine waves, allowing for simpler control of DC switched currents

6) Improving the accuracy to less than 5° achieved in this dissertation

7) Developing a method to determine clockwise vs counterclockwise rotation
REFERENCES


