MAGNETIC LEVITATION AND ROTATION FOR THE FEASIBILITY OF FREE-FORM MACHINING

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MAGNETIC LEVITATION AND ROTATION FOR THE FEASIBILITY OF FREE-FORM MACHINING

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SUMMARY

The geometric constraints of the machine tool provide a guided movement of the parts of the machine. Therefore, the relative movement between the workpiece and the cutting tool is defined as the toolpath. The toolpath is controlled or constrained by the machine to at least some extent, rather than being freehand or offhand. However, it limits the part features such as curved holes or interior surfaces in today's machining technology. In order to make it happen, we have identified the need for a new transformative manufacturing process that is capable of driving the machine tool without any support. With the uniqueness of levitation, this new transformative manufacturing process is realized.

The purpose of this thesis is to design and construct a new transformative manufacturing process using magnetic fields to levitate an object (machine tool), and test machining feasibility. This concept is based on levitation and rotation of a single abrasive particle with no support other than the magnetic field. To support the design of such a device, this thesis proposes a combination of experimental analysis and physics-based simulations. First, a vertical magnetic field will impose a vertical physical force to balance gravity and suspend the cutting tool, which has a shape of circular disk with 3 to 5 mm sharp edges. It is levitated under the non-contact magnetic force from a magnetic field generator base loaded with a constant power that creates peak magnetic field intensity at the desirable vertical nominal tool position. The cutting tool then spins under the control of an alternating magnetic field established by two pairs of pairwise orthogonal Helmholtz coils. This Helmholtz coils setup is used in a horizontal configuration to generate the rotating magnetic field (RMF) that drives the cutting tool rotation. The spinning motion enables the cutting tool with sharp edges to act as a cutting tool that is capable of plowing and removing materials from the workpiece that comes into its engagement. System configuration will be presented in this thesis to show the uniqueness of this unconventional tooling methodology. In addition, a dispositive device permitting the rotation of the levitron is integrated into the device in order to achieve higher tool rotation speed. Physical based finite element simulations based on Biot-Savart law were conducted to explore the magnetic field and help to simulate the magnetic field and position the cutting tool.

An investigation was also conducted on the magnetic shielding materials. These materials do not block the magnetic field, but rather provide a path for the magnetic field lines around the shielded volume. Experiment also shows that the magnetic field generator base, which contains one ring permanent magnets and four other electro-magnets, is able to provide sufficient vertical force to suspend the cutting tool. In addition, the two orthogonal pair-wise Helmholtz coils create a uniform rotating magnetic field at the center location. This rotating magnetic field has a moving polarity that is capable of generating rotation to a bar magnet. The results of this study show that a smooth and controlled cut can be achieved on a soft material, which is capable of addressing the design objective. This shows the feasibility of the device to achieve similar results as a machine tool.

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

In the context of manufacturing, the presence of a spindle constrains the movement of the machine tool to rotate around a fixed axis during the manufacturing process. Even with this realization, the current machining tool design has not significantly changed in decades. Despite the revolutionary advancement in machine tool design and capabilities in recent years, the development of new and innovative techniques has not been the focus of research and development. Generally, the manufacturing of products with fine and intricate geometrical details has been challenged by ultra-high precision. Feature size and line width requirements for micro devices can oftentimes be at submicron or nano metric levels and free-form flexibility. Fine details on manufactured products can be difficult-to-reach as many are internal, concaved, or reentrant features clustered within tight spaces [1]. However, the increasing demands for accuracy, finish, and free-form flexibility have pushed the capability of most traditional and non-tradition manufacturing methods to their limits, with little rooms for further improvement. The example applications that require free-form finishing are boat hulls, cutting tool, turbine blades, and airfoils. On the other hand, certain internal features of workpieces are difficult to manufacture today and widely used in medical field and food industry, such as catheter shafts, needles, capillary tubes, and curved pipes.

Current magnetic-field-assisted machining applications are mainly for the process of finishing and polishing. Many of the early fundamental theories and operational principles have been first provided by Shinmura *et al*. [6] and Kamanduri *et al.* [7]. Since

1981, researchers in Japan have developed the process and have succeeded in pursuing industrial uses [9]. As the physical mechanism becomes better understood, the magneto-abrasive machining has increasingly received attention for several practical applications in the industry [7 10 11]. However, the current magneto-abrasive technology is limited to polishing and finishing of large surface areas, and is not suited for cutting. The current methodology cannot be utilized to improve feature generation because of the difficulty of controlling the random motion. Therefore, it can only be applied to a large external or internal area. In addition, a large number of particles are used to generate the random sliding, rubbing, and plowing motions. Depth and width of cut are difficult to be evaluated with these random motions. The technical concept proposed in this research is fundamentally different from the current magneto-abrasion methods. First, while the existing methods all involve no particle rotation, the proposed concept utilizes the rotation of the cutting tool as the primary machining motion. Second, while the earlier magneto-abrasive systems use a large number of particles, the proposed concept uses only object (cutting tool), thereby overcoming the key difficulties of machining flexibility. This device aims to lead to a technological breakthrough by overcoming the limitation of the workpiece features, and achieve greater free-form machining capability.

1.2 Objective and Goals

The objective of this research is to establish a new class of manufacturing methodology for free-form machining by using electro-ferromagnetic fields to simultaneously levitate and rotate a object in performing the cutting action while engaging into a workpiece. The research is expected to potentially establish an innovative machining paradigm and open opportunities that cannot be delivered by other traditional manufacturing process. It uses one magneto-abrasive object as the cutting tool, which is ferromagnetic with a disk shape. The cutting tool is suspended, in a non-contact manner, by a constant magnetic field, and it is also actuated to spin by another alternating magnetic field. In this configuration, a worktable can feed a workpiece to contact with the cutting tool, and the workpiece can be machined at the specified feed, depth of cut, and tool path so that machined part geometries are created in a truly three-dimensional free-form manner. In addition, this methodology addresses the issue of traditional spindle by allowing free-form flexibility through the total elimination of non-cutting tool shank and the complete avoidance of physical tool geometry on the machine. This unique configuration allows the cutter to freely cut into internal, concave, or reentrant locations without interfering with other portions of the tool or workpiece, thereby offering the solid free-form machining capability. To achieve the research objective, this project will focus on the conceptual design and experimental evaluation of the proposed system. The specific tasks for this project are:

(1) Demonstrate a method of suspending the cutting tool by an external magnetic field in a non-contact manner.

(2) Demonstrate a method of actuating the rotation as the primary motion of the cutting tool.

(3) Build a prototype machine tool for full-scale experimental testing to evaluate the concept feasibility and explore the system merits and limitations.

1.3 Research Goals

For this thesis, the primary goal is to address the project objectives mentioned before by designing a magneto-abrasive cutting machine with a capable of levitating and rotating an object for machining operation. To this end, requirements and approaches for the prototype machine will be presented. Based on those requirements, a review of Helmholtz coil and other possible alternatives will be discussed. Finally, a complete system with an actual cutting operation will be presented. Based on the result of this research, the future development could be improving the levitation and rotation capabilities, and minimizing the cutting tool to further achieve micro-machining. However, it should be noted that the scope of this thesis is limited to the current status of the technology and nature of magnetic field. This research will conclude with a final design configuration, simulation and experiment.

1.4 Thesis Outline

The following is a general outlook of this thesis. Chapter 2 presents a literature review, which includes relevant publications and other applications that are related to this research. Chapter 3 summarizes the various concepts that were explored in developing the system. Chapter 4 contains experiment and simulation that were investigated during the project. Finally, Chapter 5 presents the conclusions and recommendations for future work in magnetic levitation and rotation for machining operations.

CHAPTER 2

LITERATURE REVIEW

To develop a comprehensive and innovative design, a review of the existing state-of-the-art technology is needed. This chapter presents a brief review of the relevant research that has preceded this work. This chapter contains an overview of the current view of magnetic field-assisted machining and an introduction of Helmholtz Coil pertaining to the characteristics of a magnetic field generator.

Predominately, prior work focused on applying Helmholtz Coil as the driving force of micro-machine and fish-robot, as well as investigations of multi-axis Helmholtz Coil. This research will adapt two-axis Helmholtz coils to drive the primary machining motion. The current free-form surface is also known as sculptured surface or contoured surface. It has been widely seen and used in various engineering applications such as boat hulls, cutting tool, turbine blades, and airfoils. Free-form surfaces are manufactured by additive manufacturing and sometimes by five- axis CNC machining. Unlike objects that are composed of simple geometric primitives, such as planes, lines, spheres and cylinders, free-form objects often have no obvious feature points. Therefore, they are more difficult to define, model, and manufacture than simple geometric objects.

2.1 Current View of Magnetic Field-assisted Machining

The manufacturing process of adapting magnetic fields to create the mechanical motion of cutting tools against a workpiece has been referred to magnetic field-assisted machining [1], electro-ferromagnetic machining [2], or magneto-abrasive machining [3]. Applications for these concepts are mainly for the process of finishing and polishing [4-

8]. Since 1981, researchers in Japan have developed the process and have succeeded in pursuing industrial uses [9]. Much of the early fundamental theories and operational principles have been first provided by Shinmura *et al*. [5] and Kamanduri *et al.* [6]. As the physical mechanism becomes better understood, the magneto-abrasive machining has increasingly received attention for several practical applications in industry [7 10 11].

In 2001, a group in Egypt came with a concept of magnetoabrasive finishing process by conducting a flexible finishing action that is exerted by a blanket of abrasives bounded to iron particles. [3] The concept of the process is shown in Figure 2.1. "Magnetoabrasive finishing cutting agent is a composite of fine abrasive grits and coarser iron grains. The particles can thus be excited by a strong magnetic field to generate a normal dynamic pressure sufficient to refine the surface, deburr and chamfer its edges." [3]

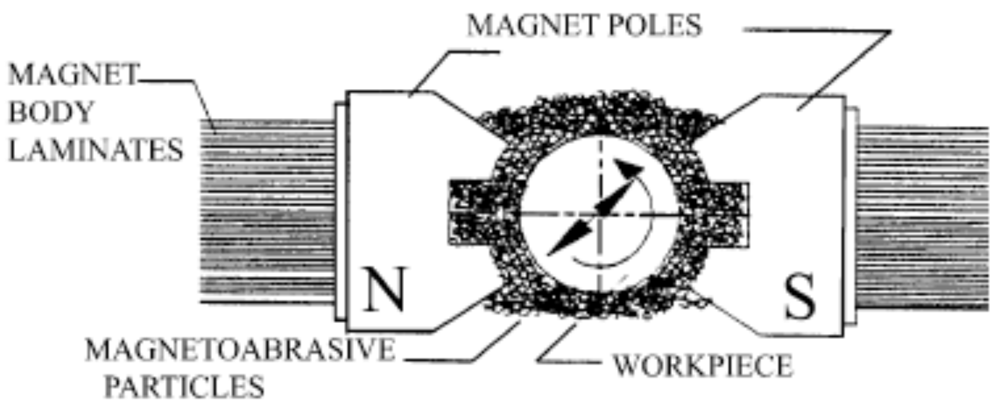

Figure 2.1: Finishing zone in Magnetoabrasive Finishing (MAF) [3]

Later, a group in Japan developed a new process using an alternating magnetic field to control magnetic tools inside of the workpiece. The theory of the process is shown in Figure 2.2.

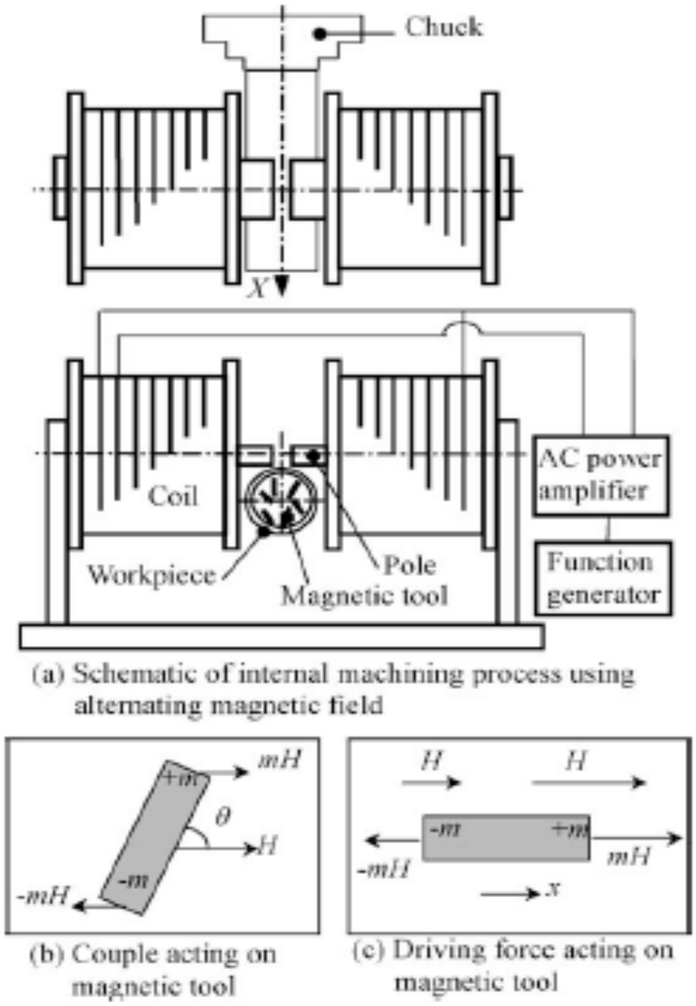

Figure 2.2: Schematic of Schematic of Internal Machining Process [12]

This setup is done by placing different coils facing each other in a parallel manner in order to generate an alternating magnetic field around two magnetic poles. The two poles are positioned directly above the workpiece with an adjustable interpole separation. The machining tools, such as pins, are inserted into the workpiece and excited by the alternating magnetic field. This process has characteristics of:

- Internal precision machining process with multiple pins.
- Controlling machining tool by alternating magnetic field and geometry of the tools.

- Achieving the desired hardness improvement and reduce surface roughness.

However, prior process of the magneto-abrasive technology is limited to polishing and finishing of large surface areas, due to a large number of particles used to generate the random sliding, rubbing, and plowing motions.

2.2 Overview of Helmholtz Coil

The Helmholtz Coil is a device to produce a region of nearly uniform magnetic field, shown in Figure 2.3. It consists of two identical circular wire coils that are placed symmetrically one to another along a common axis with a distance. Each coil carries equally amount of current and flows in the same direction.

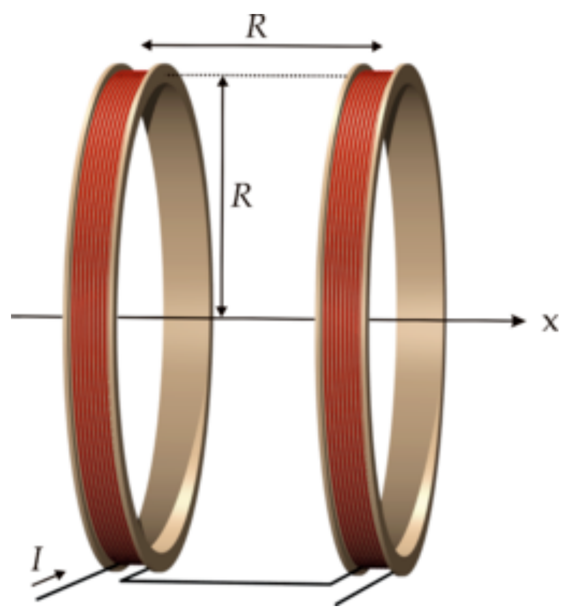

Figure 2.3: Helmholtz Coil

The magnetic field lines of Helmholtz Coil are defined based on the orientation, shown in Figure 2.4. It is seen that the magnetic field is generated with a uniform direction (to the right), and the non-uniformity of the magnetic field is minimized at the center of the coils.

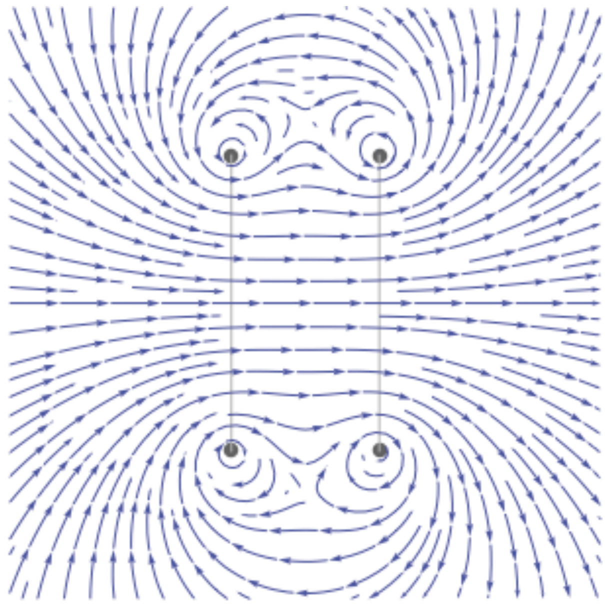

Figure 2.4: Magnetic Field Lines in Helmholtz Coil

Biot-Savart Law describes the magnetic field generated by an electric current consistent with both Ampere's circuital law and Gauss' Law for magnetism. It relates the magnetic field to the magnitude (I) and direction of the electric current, and length (R) and number of the wire loops (n). Resultant magnetic field (B) is defined in Equation 2.1.

$$B = \frac{\mu_0 n I R^2}{2(R^2+x^2)^{3/2}} \tag{2.1}$$

The permeability (μ_0) is the degree of magnetization that a material obtains in response to an applied magnetic field. For example, the value of magnetic permeability in vacuum is $\mu_0 = 1.26 * 10^{-6} [\frac{T \cdot m}{A}]$.

2.2.1 Multi- axis Helmholtz Coil

When an external rotating magnetic field is applied, there is the magnetic torque caused by the angle between magnetization and rotating magnetic field [1]. Figure 2.5 shows a three-axis Helmholtz coil, which is capable of controlling a rotating magnetic field in the X-Y plan and rotating along with Z-axis.

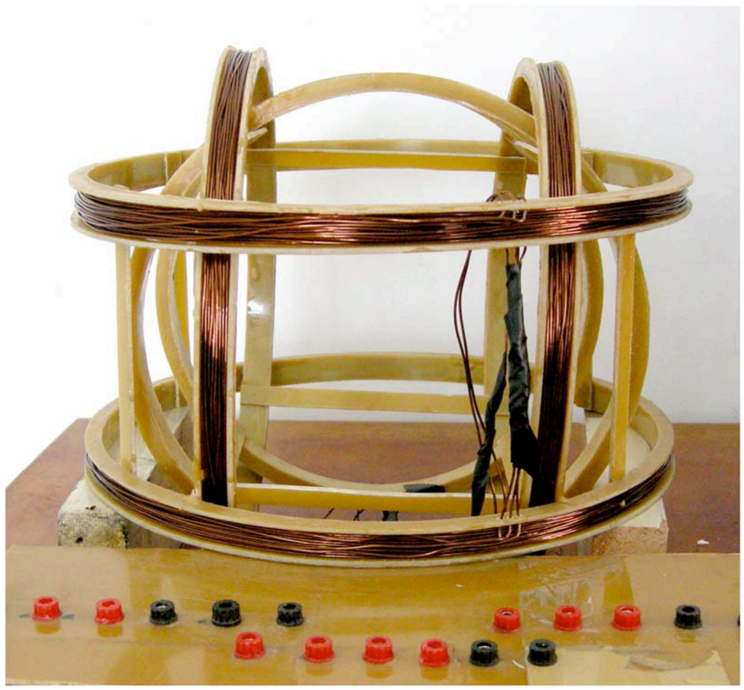

Figure 2.5: Three-axis Helmholtz Coil [14]

The magnetic flux density in X, Y, Z direction can be expressed in equation 2.2, 2.3 and 2.4. [14]

$$B_X = B_X \times cos\beta - B_Z \times sin\beta \tag{2.2}$$

$$B_Y = B_X \times sin\alpha \times sin\beta + B_Y \times cos\beta + B_Z \times cos\beta \times sin\alpha \tag{2.3}$$

$$B_Z = B_X \times sin\beta \times cos\alpha - B_Y \times sin\alpha + B_Z \times cos\alpha \times cos\beta \tag{2.4}$$

Where α and β are Euler angles and satisfied by $\beta = \frac{\pi}{2} - \theta$, $\alpha = \arcsin\left(\frac{cos\phi}{sin\theta}\right)$, and assuming $\phi = 0$. θ, ϕ, and $\varphi$are separation angels of rotating magnetic field through origin and X, Y and Z axis. The micro-machine rotates in synchronism with the rotating external magnetic filed by magnetic torque and move [14].

2.3 Summary

The current machining tool design has not significantly changed in decades with the concept of using spindle to control the rotation of the cutting tool. In recent years, magnetic field-assisted machining concept takes the advantage of adapting magnetic field to polish and finishing process, which gives space of improvement in surface finish and is able to conduct finishing process to some inaccessible surfaces. However, the increasing demands of accuracy, finish, and free-form flexibility have pushed the capability of most traditional and non-tradition manufacturing methods to their limits, with little rooms for further improvement. This chapter reviews much development and limitation related to magnetic field-assisted machining, and, more specifically, applying magneto-abrasive object to conduct manufacturing process, which have relevance to the research presented in this thesis. Initially, a review of current magnetic field-assisted machining techniques is presented. To test the feasibility of applying magnetic levitation and rotation as a cutting tool, a review of possible driven options is presented. Considerable attention is given to the Helmholtz coil. Its physical phenomena of magnetic field are capable of creating a magnetic field to generate forces acting on a magneto-abrasive object. It is found that the Helmholtz coil system has specific relevance to the proposed research to drive rotation but will create interference between two different magnetic fields, which cost a difficulty on levitation. This will be discussed later in this thesis.

CHAPTER 3

DESIGN EXPLORATION

Due to the revolutionary nature of this research, very little literature could be referenced for the design of such a unique system. Hence, different concepts and potential designs of such a system are explored and tested with various methodologies. This chapter contains an overview of different approaches used for the construction of a magneto-abrasive cutting machine in this project. The chapter will first present the proposed system configuration, along with issues that are perceived to be the primary obstacles hindering the methods of rotation. Next, the information pertaining to how the system will accomplish the tasks outlined in Chapter 1 will be covered. A detailed analysis and simulation of the design will be presented in a later chapter.

3.1 Proposed System Configuration

The proposed magneto-abrasive cutting machine is composed of a magnet attached with sharp edges and a magnetic field generator base, shown in Figure 3.1.

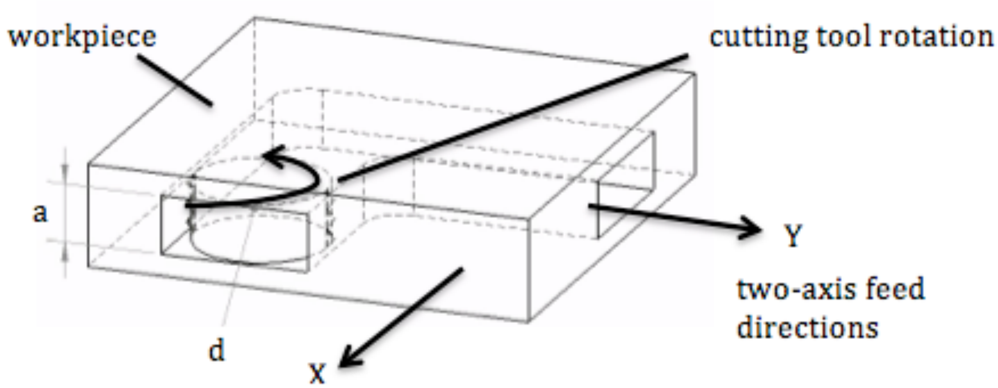

Figure 3.1: Abrasive cutting machine configuration

To achieve the cutting functions that are proposed in the beginning of this chapter, a controllable rotation and stable levitation are required.

The proposed system will provide a primary machine motion, which is capable of creating shear deformation on a soft material. Based on the physical phenomena of magnetic torque with two-axis Helmholtz coil, rotating magnetic field will be able to drive a bar magnet. This bar magnet, which contains north and south poles in horizontal manner, can be attached to a machine tool to drive the rotation, as shown in Figure 3.2.

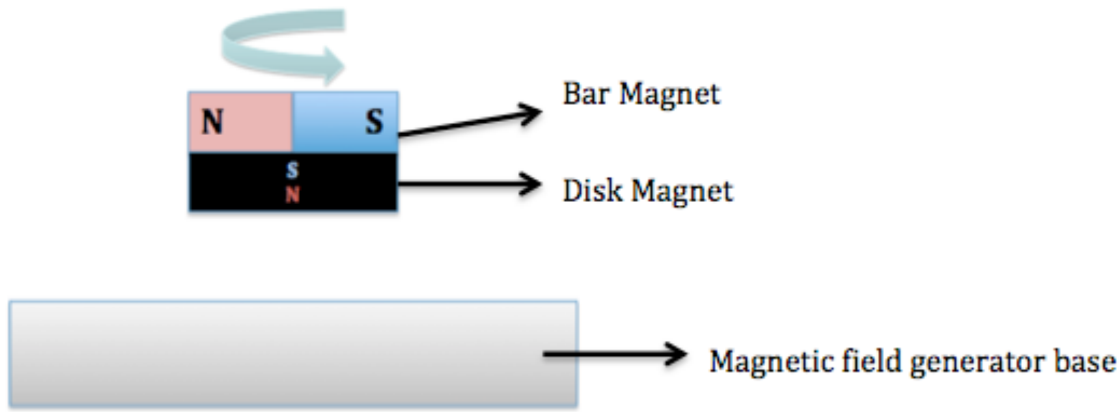

Figure 3.2: Proposed System 1

Unfortunately, the bar magnet interacts to the magnetic field generator base, which cause it to drop. This is because the north pole is attractive to the base while the south pole is being repelled from the base. To solve this problem, magnetic field shielding materials are investigated and tested with this setup, which will be presented later on in this chapter.

3.2 Construction

3.2.1 Helmholtz Coil

To generate the desired rotating magnetic field, two pairs of Helmholtz coils are attached with a 90 degrees angle, shown in Figure 3.3. Table 3.1 below shows the specifications of the Helmholtz coils purchased from 3B Scientific Physics.

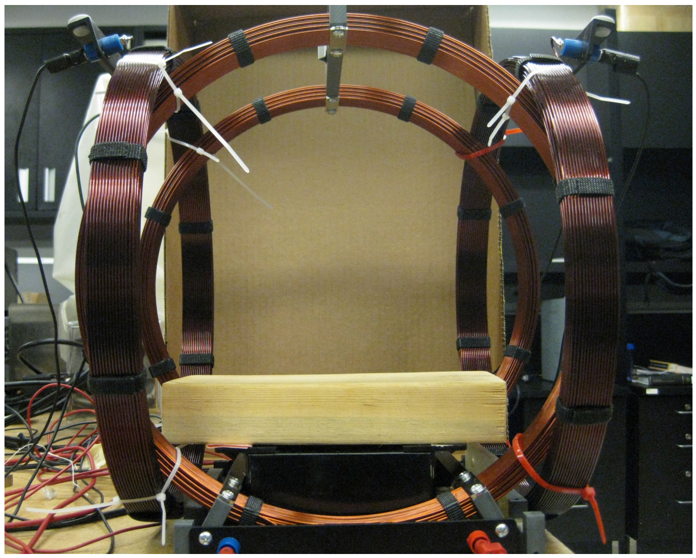

Figure 3.3: Two-axis Helmholtz Coils

Table 3.1: Helmholtz Coil Specifications

Number of turns per coil:	124
Outer coil diameter:	311 mm
Inner coil diameter:	287 mm
Mean coil radius:	150 mm
Coil spacing:	150 mm
Enamelled copper wire thickness:	1.5 mm
DC resistance:	1.2 Ohm each
Maximum coil current:	5 A
Maximum coil voltage:	6 V
Maximum flux density at 5 A:	3.7 mT
Weight:	4.1 kg

To generate the rotating magnetic field, dual-phase sinusoidal signal is chosen. In order to control the frequency and magnitude of the rotating magnetic field, a specific operational amplifier is built to ensure both of the sinusoidal waves have the same frequency and magnitude, which is critical to generate a stable rotation.

3.2.2 Electronics

The OPA541 is a power operational amplifier capable of operation from power supplies up to +/−40V and delivering continuous output currents up to 5A. This electronics and connect configuration will provide the same frequency and magnitude of the current signal to the two-axis Helmholtz coils in order to achieve rotating magnetic field, shown in Figure 3.4 and Figure 3.5.

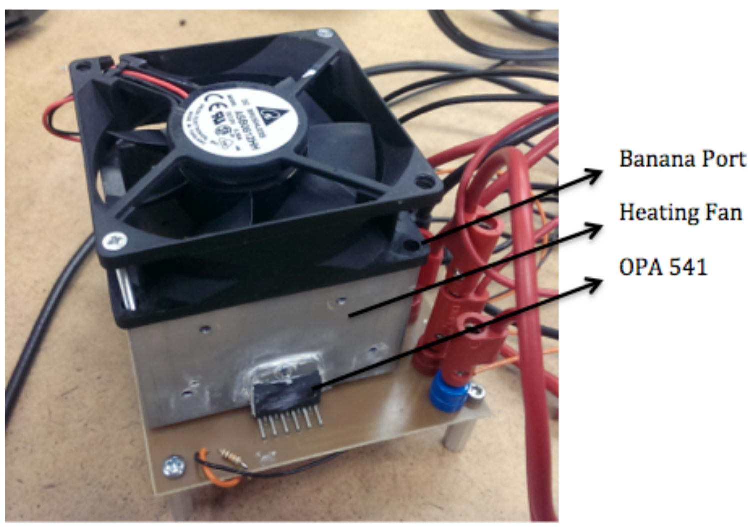

Figure 3.4: Power Electronics

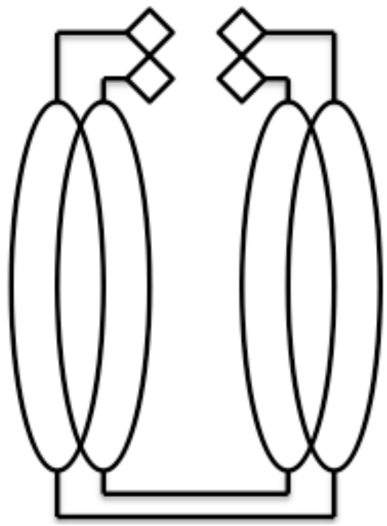

Figure 3.5: Power Connection Configuration of Two-axis Helmholtz Coil

3.2.3 Levitation & Rotation Piece

To achieve levitation and allow the cutting tool entirely free-hand, a disk magnets with north pole and south pole are distributed in vertical direction, as shown in Figure 3.6. From the nature of the magnetic field, same polarity will repel each other; on the other hand, opposite polarities will attract each other.

Figure 3.6: A Disk Magnet with Polarity in Vertical Direction

Two different neodymium bar magnets are used and tested in order to achieve the desired rotation of the cutting tool, shown in Figure 3.7. It is the most widely used type of rareearth magnet, and is a permanent magnet made from an alloy of neodymium, iron and boron to form the $Nd_2Fe_{14}B$ tetragonal crystalline structure. Neodymium magnets are one of the stronger types of permanent magnets.

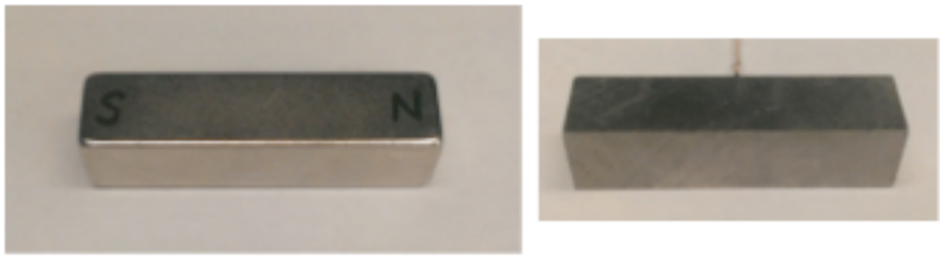

Figure 3.7: Neodymium Bar Magnets with Polarity in Horizontal Direction

Table 3.2: Magnets Specification

	Disk	Bar 1	Bar 2
Dimensions (in)	1.57 x 0.385	½ x ½ x 2	0.375 x 0.375 x 1.5
Weight (g)	83.5	61.3	25.6

3.3 Design Issues

As mentioned before, two-axis Helmholtz coils can generate rotating magnetic field to drive a bar magnet. This bar magnet can attach to a machine tool to drive the rotation. However, problems arise due to the interference between two different perpendicular magnetic fields, which cost the floating piece to drop. This problem will be discussed below in order to arrive at a better understanding of the issue at hand.

3.3.1 Magnetic Shielding

In order to eliminate the interaction between the levitation and rotation piece, magnetic shielding is tested. F.W.-Bell gauss/ teslameter model 5070 shown in Figure 3.8 is used to measure the performance of the magnetic shielding material.

Figure 3.8: F.W.-Bell Gauss/ Teslameter Model 5070

Attenuation is the ratio of the magnetic field strength on one side of the foil compared to the field strength on the side within a cylinder closure. It is calculated by foil thickness (t), permeability (μ), and diameter of the cylinder closure (D), defined in Equation 3.1.

$$A = t \times \mu / D \qquad (3.1)$$

Magnetic shielding made of high magnetic permeability metal alloys can be used, such as sheets of Permalloy and Mu-Metal, or with nanocrystalline grain structure ferromagnetic metal coatings as shown in Table 3.3. These materials do not block the magnetic field, as with electric shielding, but rather draw the field into themselves, providing a path for the magnetic field lines around the shielded volume. The best shape for magnetic shields is thus a closed container surrounding the shielded volume. The effectiveness of this type of shielding depends on the material's permeability, which generally drops off at both very low magnetic field strengths and at high field strengths where the material becomes saturated. As a result, to achieve low residual fields, magnetic shields often consist of several enclosures, having one inside the other, and each of which successively reduces the field inside it.

Table 3.3: Shielding Material Comparison

Strong Field	Weak or Moderate Fields	High Frequency Fields
>1 Gauss	Milli-Gauss Levels	kHz, MHz
Low permeability alloys	High permeability alloys	
Giron	Mu-Metal	Nanocrystalline magnetic shielding alloy sandwiched between layers of clear PET (Polyethylene terephthalate)

Mu-metal is selected based on the measurement of the magnetic field from the floating piece. Mu-metal is a range of nickel-iron alloys that are notable for their high magnetic permeability, composed of approximately 77% nickel, 16% iron, 5% copper, and 2% chromium or molybdenum. The high permeability of mu-metal provides a low reluctance path for magnetic flux, leading to its major use, in magnetic shields against static or slowly varying magnetic fields. It does not block magnetic fields but provide a path for the magnetic field lines around the shielded area. Figure 3.9 below shows the effectiveness of the shielding material by applying different layers of it. It was found that the magnetic flux density could be reduced by 50% when five layers of shielding material were attached on top of the floating piece.

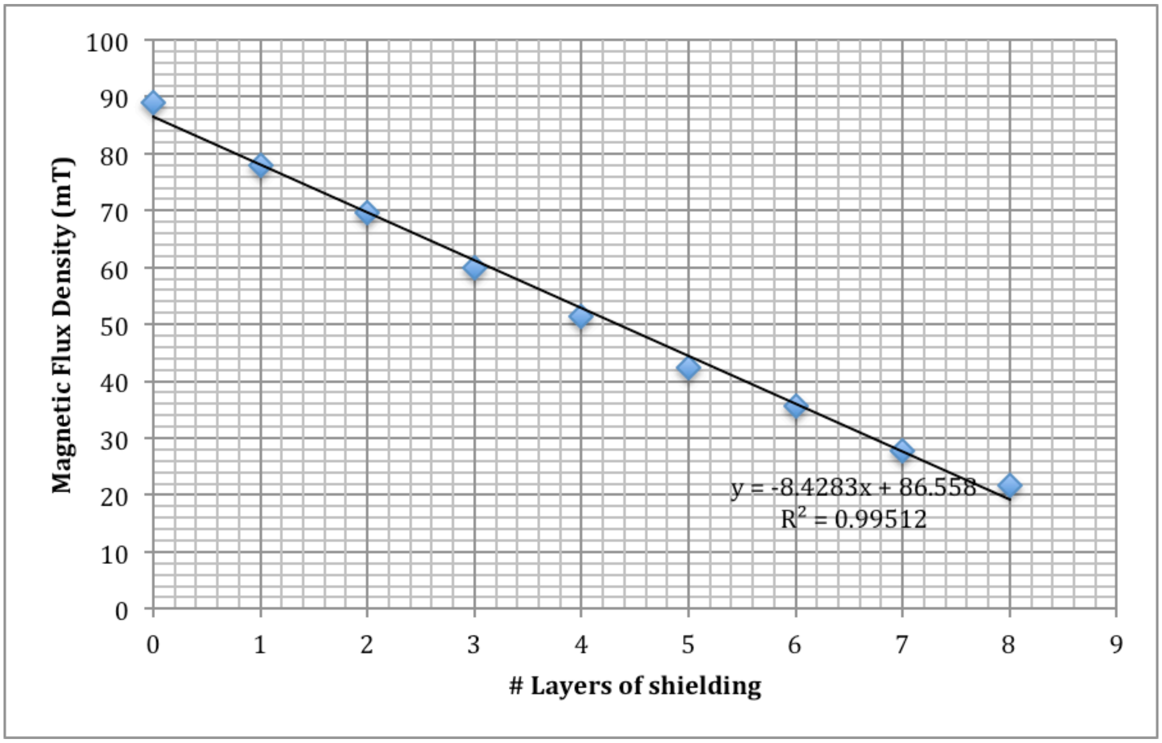

Figure 3.9: Plot of Magnetic Flux Density vs. Layers of Shielding Material

Magnetic shielding material was also tested with bar magnets to see whether magnetic flux could be effectively reduced in order to achieve stable levitation. The position of the measurement is shown in Figure 3.10 and results are shown in Table 3.4.

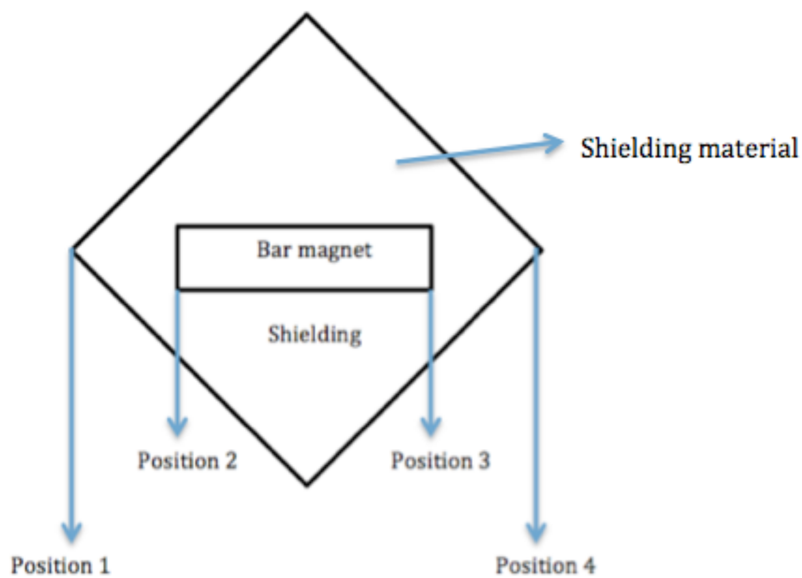

Figure 3.10: Locations of Measurement on Magnetic Shielding

Table 3.4: Results of Measurements on Magnetic Shielding

	Position 1	**Position 2**	**Position 3**	**Position 4**
No shielding	-31.5 mT	-49.7 mT	72.4 mT	58.5 mT
1 layer (0.63 mm)	-21.3 mT	-16.6 mT	57.3 mT	21.4 mT
2 layers (1.20 mm)	-1.25 mT	-1.89 mT	5.83 mT	4.66 mT
3 layers (1.73 mm)	-0.30 mT	-0.24 mT	0.33 mT	0.63 mT

It was observed that the bar magnet contained unevenly distributed magnetic field, with the south pole dominated by the north pole. Ten layers of shielding material were applied to the floating piece and bar magnetic, and tested with the magnetic field generator base. By observation, the cutting tool was able to achieve stable levitation for approximately 1.5 min until the saturation, which caused it to drop. Further study is conducted by COMSOL Multiphysics simulation in Chapter 4.

CHAPTER 4

EXPERIMENT AND SIMULATIONS

This chapter contains experimental and simulated results of different sub-systems. First, magnitude of the rotating magnetic field is evaluated and tested with bar magnet, which demonstrates a method of actuating the rotation as the primary motion of the cutting tool. A new transformative manufacturing methodology is then introduced. The cutting device is comprised of a magnetic field generator base to levitate the cutting tool, and a rotation motion control using a rotating surface. Moreover, study of simulation in COMSOL software is conducted. Finally, the proposed prototype machine demonstrates the feasibility of achieving similar outcomes as a machine tool.

4.1 Helmholtz Coil Experiment

The experiment first investigates the difference in field between the center and the planes of the coils, uniformity, and the properties of rotating magnetic field. Measurements were conducted with gauss-meter to evaluate the magnitude and direction of the Magnetic flux density. Magnetic flux density is measured by varying the current through the two pairwise Helmholtz coils and the frequency of the sinusoidal wave, shown in Table 4.1 and Table 4.2. The measurements were conducted in the center of the coils, as shown in Figure 4.1.

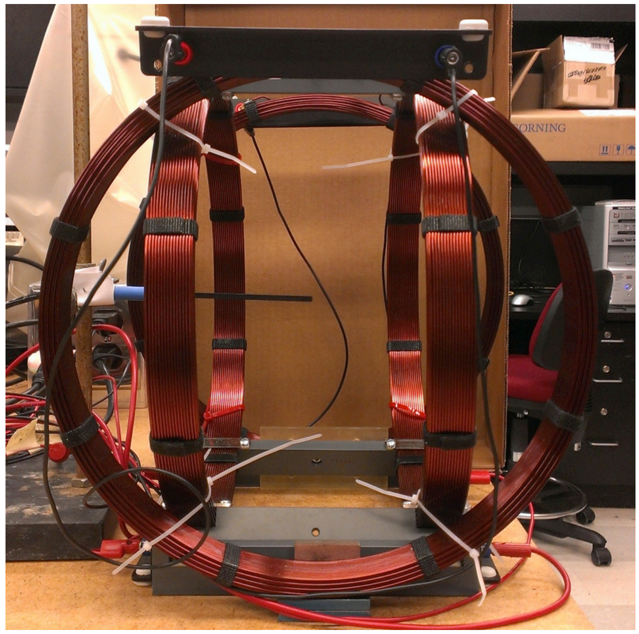

Figure 4.1: Experiment Apparatus 1

Table 4.1: Magnetic Flux Density Measurement

Current (A)	Tesla (mT)
0.1	0.078
0.2	0.156
0.3	0.234
0.4	0.312
0.5	0.390
0.6	0.468
0.7	0.546
0.8	0.623
0.9	0.701
1	0.779
1.1	0.857
1.2	0.935
1.3	1.013
1.4	1.091
1.5	1.169

Table 4.2: Magnetic Flux Density Measurement

Hertz (Hz)	Tesla (mT)	Hertz (Hz)	Tesla (mT)
40	1.753	130	0.819
50	1.650	140	0.707
60	1.545	150	0.593
70	1.435	160	0.496
80	1.337	170	0.385
90	1.229	180	0.282
100	1.127	190	0.175
110	1.098	200	0.071
120	0.913		

As seen from the quantitative results in Table 4.1 and 4.2, the magnetic flux density increases with the increasing current while keeping the frequency constant. Secondly, it is difficult to keep the current constant while varying the frequency of the signal. By reducing the frequency of the signal, the current through the Helmholtz coil increases, which boosts the strength of the magnetic flux density. The bar magnet is then attached with a string and positioned in the center of the Helmholtz coil to investigate how the strength in magnetic flux density influences the rotation. The result will be presented in the later section of this chapter.

4.2 Levitation Experiment

The purpose of this loading test is to determine the system's behavior under both normal and anticipated peak load conditions. This helps to identify the maximum operation capacity of the levitation system. Loading experiment is conducted to ensure the floating piece is capable of taking load from additional features such as cutting edges and rotational piece. The experimental apparatus is shown in Figure 4.2.

Figure 4.2: Experiment Apparatus 2

Loading test was done by adding different amount of weights on the top surface of floating piece until it dropped. Weights were ranging from 0 to 500 grams. By observation, the floating piece was able to take an additional load without dropping at the maximum of ~340 grams. From the result we presented earlier, it gives us confidence of the situation of disturbance during rotation or cutting. This also shows the ability of magnetic field suspension for the cutting tool.

4.3 Rotation Experiment

To act as a machine tool, a primary motion is required as explained in early chapter to make shear deformation to the workpiece. As mentioned before, two orthogonal pairwise Helmholtz coils are used to generate the rotation magnetic field. This section presents two different rotation experiments. First, the rotation driven mechanism, which is the bar magnet with a dimension of 1.5 inches in length, 0.375 inches in width and 0.375 inches in height, was tested with the rotating magnetic field generated by the two pairwise Helmholtz coils. The system apparatus is shown in Figure 4.3.

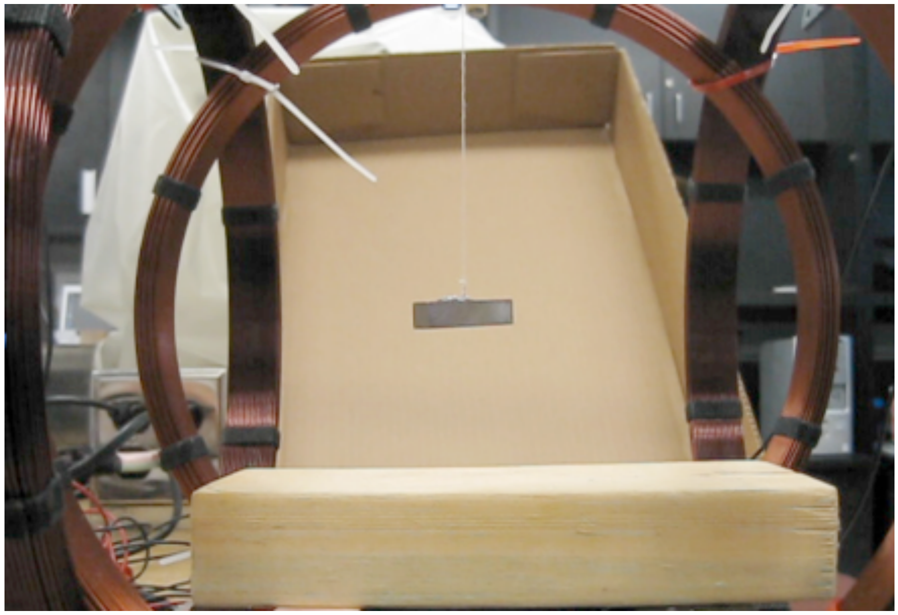

Figure 4.3: Rotation Experiment Setup with Bar Magnet

It was seen that the rotating magnetic field was generated and able to drive the rotation of the bar magnet successfully by varying the magnitude and frequency of the signal. The rotation was observed ranging from 40-60 RPM.

However, the two pairwise Helmholtz coils gave a huge disturbance to the levitation system, which caused it to drop right after the power supple was switched on. With that in mind, a preferred orientation between the floating piece and the magnetic field generator base was found by observation. To test the strength of this nature of the device, a DC motor was attached to the generator base, shown in Figure 4.4. With a portable power for the magnetic field generator base, rotation speed measurement was taken by using AGPtek Digital Laser Photo Tachometer.

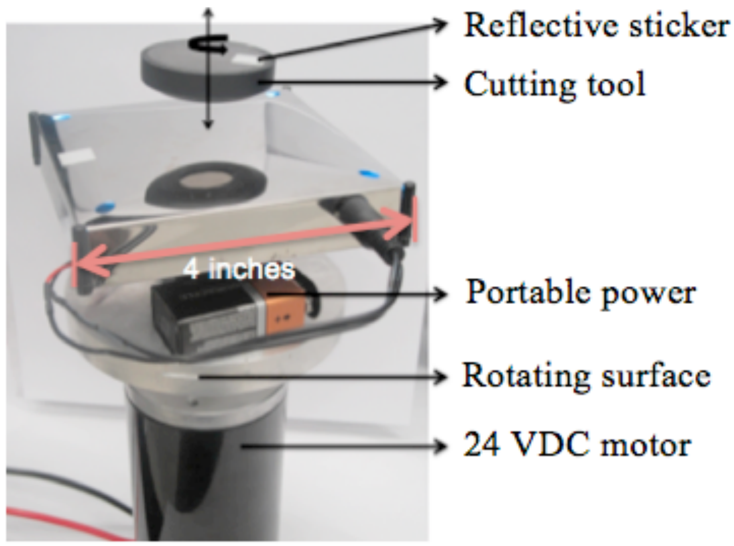

Figure 4.4: Machine model and cutting tool motion

Controllable rotation of the cutting tool was developed and shown in Table 4.3. It was observe that the cutting tool was able to follow the rotation of the magnetic field generator base with up to 88 RPM plotted in Figure 4.5.

Table 4.3: Relative rotation speed between MF generator base and the cutting tool

Voltage (V)	Motor (MF generator base) Rotation Speed (RPM)	Cutting Tool Rotation Speed (RPM)
2	6	0
6	19	18
9	30	28
12	42	41
15	55	53
18	67	64
21	76	76
24	85	88

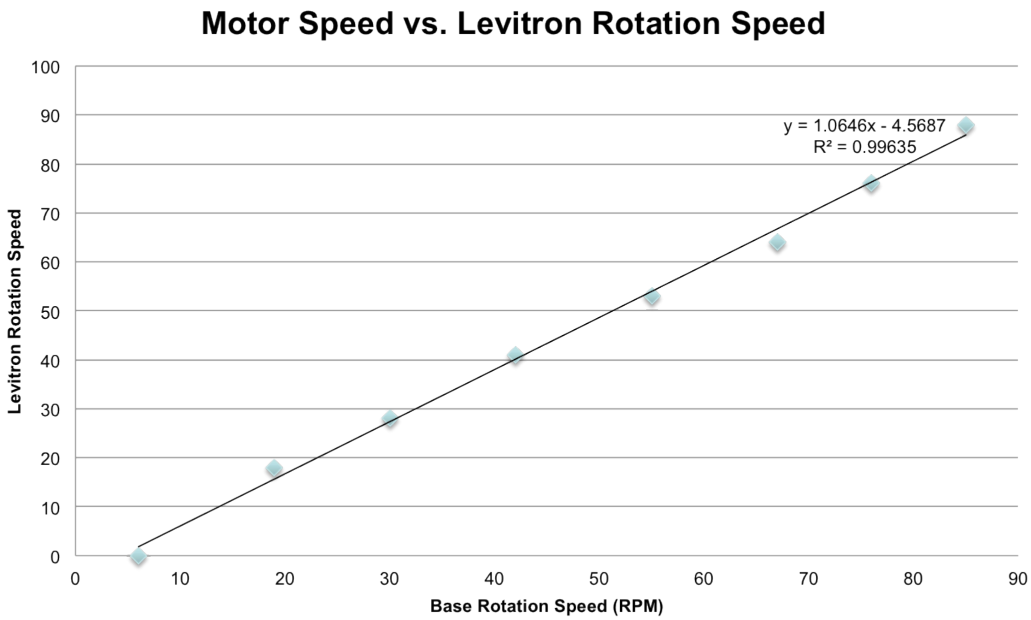

Figure 4.5: Plot of Motor Speed vs. Cutting Tool Rotation Speed

With this controllable rotation ranging from 18 RPM to 88 RPM, another motor was installed and tested. It was observed that the rotation reached a maximum approximate to 119 RPM before it dropped. This could be because of the centrifugal force was drawing the rotating body away from the center of rotation.

Based on the uniqueness of the preferred orientation between the magnetic field generator base to the cutting tool, the primary machining motion was established from 18 RPM to 119 RPM. As mentioned before, with levitation and rotation, this device is capable of conducting a small amount of shear force to the soft workpiece.

4.4 Cutting Experiment

The purpose of this test will experimentally verify the feasibility of free-form machining. The input-controlling factor is DC voltage power and outputs are cutting tool rotational speed, steady state rotational stability, and positioning stability. The cutting experiments were conducted on a single-axis worktable to deliver workpiece movement relative to the cutting tool. A soft material was selected as a workpiece to test the feasibility of cutting. The speed of rotation decreases significantly once the cutting tool makes the first contact to the workpiece. A cut is defined when a visible mark/ scratch is established. Each different orientation of the sharp edges and rack angles was attached to the floating piece, as shown in Figure 5.6, in order to create shear deformation on the workpiece. The sharp edge was a selected non-ferrous material of aluminum sheet with thickness of 0.1016 mm.

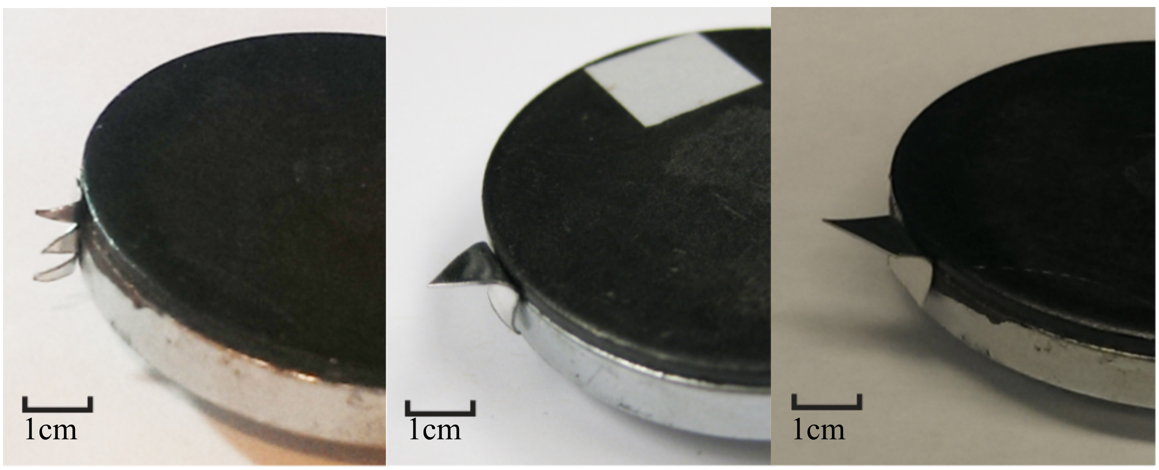

Figure 4.6: Different Sharp Tip and Rack Angle Design for Cutting Tool

Jelly was chosen as a workpiece to test the cutting ability. It has an approximate density of 0.997 g/cm^3 and Young's modulus of 0.1 MPa. The workpiece was placed on the top of a worktable, which is capable of engaging the workpiece linearly in one direction. Different cutting experiments were tested with different cutting speed and different feed. A defined cut could not be established when the rotation is below approximately 70 RPM. This is because the cutter is not able to provide sufficient force to create shear deformation against the workpiece surface. A good quality cut can be established with 109 RPM, as shown in Figure 4.7.

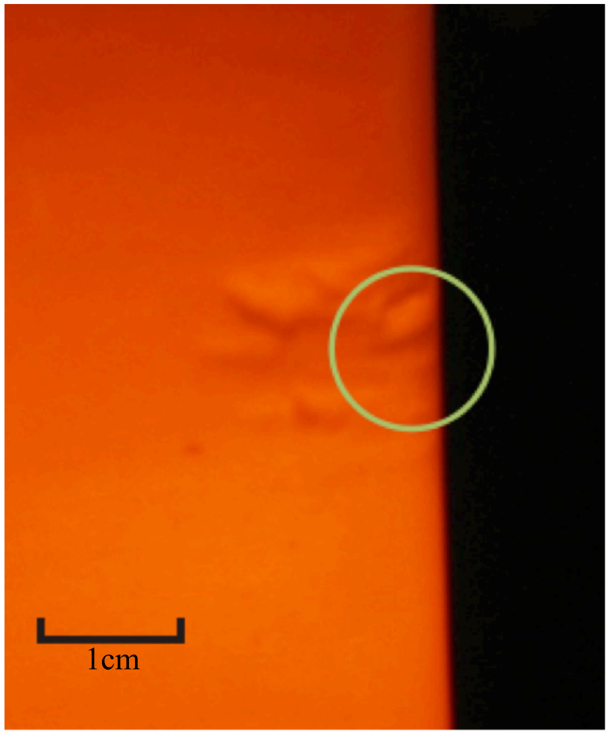

Figure 4.7: A Quality Cut with 109 RPM

The prototype magneto-abrasive cutting machine was comprised of a magnetic field generator base to levitate the cutting tool, and a rotation motion control using a rotating surface. In the cutting experiment, it was capable of providing sufficient shear force to create shear deformation on jelly. This demonstrates the possibility of applying such a unique device to make a defined cut.

4.5 Simulation

Simulation study was conducted in COMSOL Multiphsics in order to see why the floating piece dropped when there was a current through the Helmholtz coils. This simulation would indicate the magnitude and direction of the magnetic flux density in the Helmholtz coil. The Helmholtz coil field generation can be static, time-varying DC, or

AC, depending on the applications. In our research study, we adapted two sinusoidal waves with a 90 degrees phase shift in order to generate rotating magnetic field. This model uses the permeability of vacuum, which is $\mu = 4\pi*10^{-7}$ [H/m]. The external current density is computed using a homogenized model for the coils, each one made by 124 wire turns and excited by a current of 900 mA. The currents are specified to be parallel for the two coils. The model was built using the 3D magnetic fields interface. The model geometry is shown in Figure 4.8.

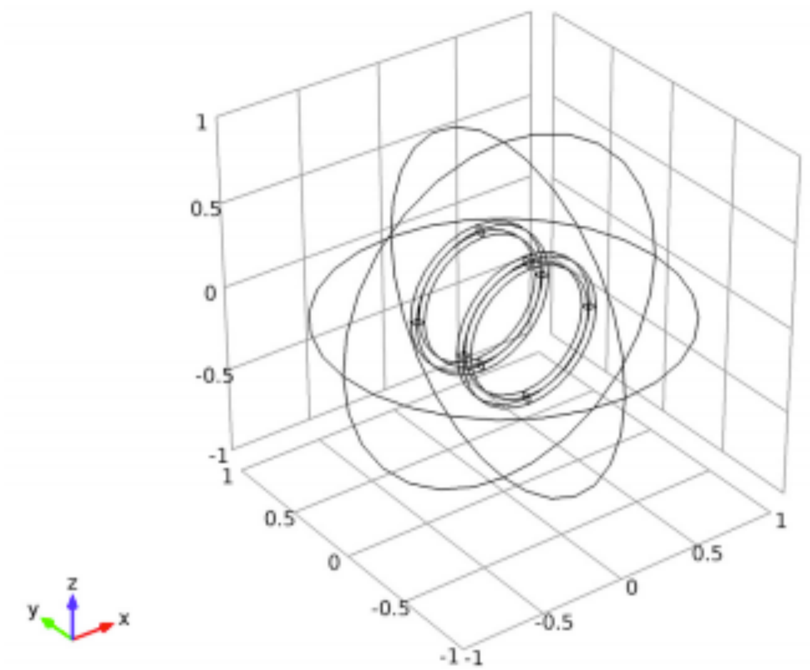

Figure 4.8: The Model Geometry

Figure 4.9 shows the magnetic flux density between the levitation setup and the Helmholtz coils. The arrows show the directions of magnetic field, while the color red indicates strong magnetic field (~80 mT) and green indicates weak magnetic field (~0.75 mT). It is seen that the levitation setup, which is driven by the vertical magnetic field, is dominant significantly. This creates huge interference with the magnetic field generated by the Helmholtz coil, which causes the cutting tool to drop when there is enough current going through the Helmholtz coil.

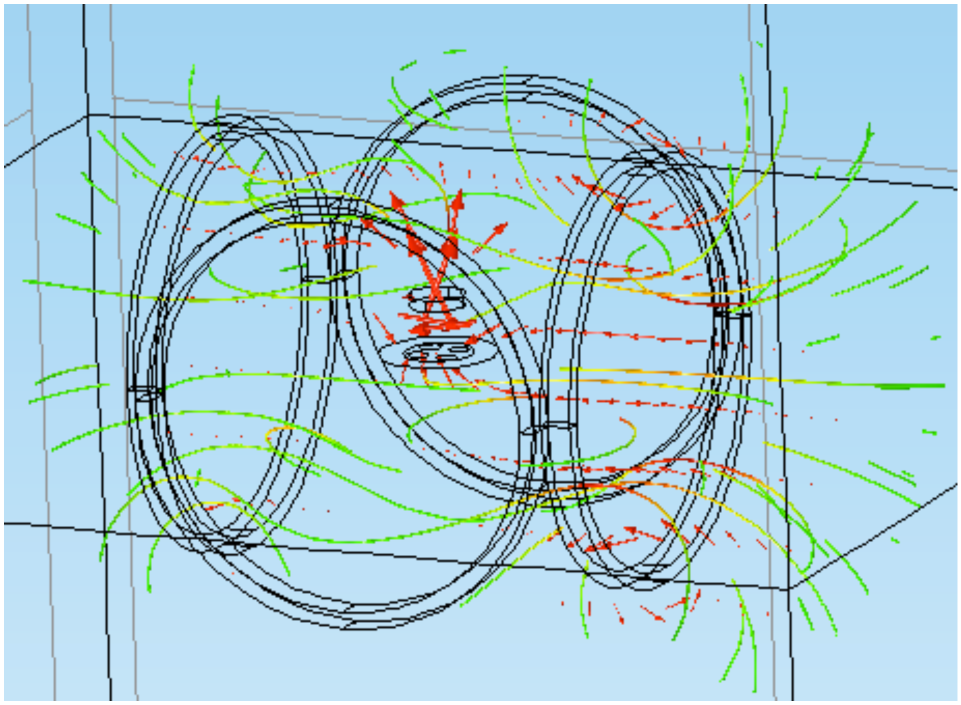

Figure 4.9: COMSOL Multiphysics Simulation

From the simulation, it is seen that the magnetic field generator base, which contains one ring permanent magnet and four other electro-magnets, is providing sufficient vertical force to suspend the cutting tool. Second, the two orthogonal pair-wise Helmholtz coils create a uniform rotating magnetic field at the center location. To retain stable levitation of the cutting tool, the magnetic effect from rotating magnetic field needs to be eliminated. Further discussion and recommendation will be presented in a later chapter.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This thesis presents a design of applying magnetic levitation and rotation to achieve a machining operation. To this end, the research describes a general approach to final device based on the requirement specifically for such a system. A cutting device was developed with special attention given to investigation on magnetic shielding material and Helmholtz coil, which were the crucial system bottlenecks. The following research topics are addressed in the course of this research work:

- A comprehensive review of relevant research in the field of magnetic field driven machining system is presented in chapter 2. An initial review of Helmholtz coil is presented with applications of generating a rotating magnetic field. A discussion of these systems is presented in the context of this research study. It is found that the Helmholtz coil system has specific relevance to the proposed research to drive rotation but will create another difficulty on levitation.
- Study of levitation and rotation are presented as design requirement for such a device. Attentions then focus on Helmholtz coil and rotating magnetic field, which was originally the main drive of this research. A discussion of the physics is presented in order to quantify the system. An investigation was also conducted on the magnetic shielding material. These materials do not block the magnetic field, but rather provide a path for the magnetic field lines around the shielded volume. Due to this material property, it is difficult to levitate and rotate the cutting tool at the same time.
- Different design concept alternatives are investigated in Chapter 4. A detailed construction of the system and design exploration is reviewed in the context of the

objective outlined for this research. A determination process is mentioned based on the difficulties encountered during the experiment observation. After series of tests and measurements, a new transformative manufacturing methodology was introduced. The new cutting device is comprised of a magnetic field generator base to levitate the cutting tool, and a rotation motion control using a rotating surface. Moreover, study of simulation in COMSOL software was conducted. From the simulation, it was observed that the two different magnetic fields with different direction interfere with each other, which creates difficulty to retain stable levitation of the cutting tool while rotate it with rotating magnetic field. Finally, the proposed prototype machine demonstrates the feasibility of achieving similar outcomes as a machine tool.

The proposed machine is unique because other magneto-abrasive machining can only perform random motions on the abrasive particles. This methodology may be useful for the future technology of making special features, such as curve holes and interior surface. This study opens opportunities in semiconductors, information appliances, energies, consumer electronics, precision machineries, and biomedical systems in the future.

Based on the results of this research study, future work can focus on the following:

- The rotation speed on the cutting tool can be improved, which currently hinders the feasibility of performing cutting operation other than jelly. To do so, three pair-wise Helmholtz coils can be used instead of two pairs. The three coils can be driven with each set being 120 degrees in phase from the others.
- Electromagnetic shielding (also known as RF shielding) and/ or eddy currents

could be other options for canceling the applied magnetic field rather than providing a path around the magnetic shielding material.

- Different controlling parameters can be tested, such as machine tool size, Helmholtz coil-turns, and current frequency.
- Numbers of hall sensors in different locations in the Helmholtz coil can be implemented to define a better quantitative understanding of the rotating magnetic field.
- Investigation can be conducted on how to apply magnetic shielding materials to COMSOL simulation.

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