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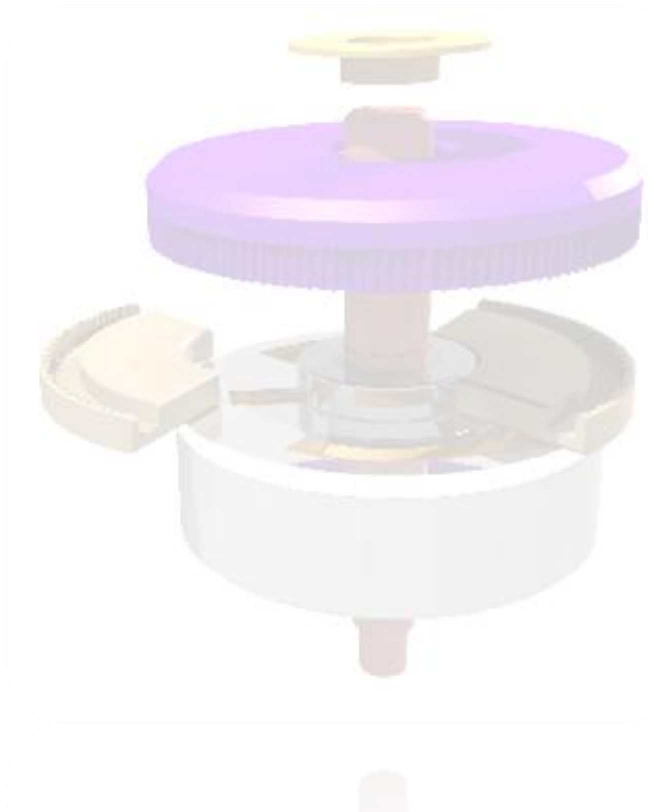

THESIS DOCUMENT

Electromagnetic-Permanent Magnet Clutch Design

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Many thanks to

Professor W.L. Cleghorn, Professor Mills, Ontario Centre of Excellence, MIE Department, MC72 Machine Shop staff, and department of Power Systems at Magna Closures

Abstract

The GM-T900 Power Liftgates, designed and manufactured by Magna Closures (Industry Partner), allow for automatic opening and closing of rear vehicle gates (SUV Trunk Lid). The GM-T900 Power Liftgate assembly uses Serration Clutch Design (Teeth Plated Clutch) to transfer torque through the DC motor to the output crank arm of the Power Liftgate. The clutch assembly allows for manual operation of the rear gate of the vehicle in case of emergency or any failure.

The Electromagnetic Clutch assemblies used in the GM-T900 Power Liftgates are designed to be controlled using electronic control modules and come with a significant disadvantage: a limited allowable engagement duration. This physical limitation results in a maximum amount of time in which the coil of the clutch assembly can be energized due to heat generated in the coil. It is however ideal to use Electromagnetic Clutch Assemblies in order to easily control the Gear Motor Assembly. The next-generation Power Liftgates, designed by Magna, allow for a new feature called the Third Position Hold option. This feature allows the driver to program the Power Liftgate and select any open or close gate traveling angles, meaning short garage ceiling and such will not be a problem for the opening gate trunk.

Nevertheless, the Third Position Hold Power Liftgate requires a clutch assembly that has no engagement time limit. The current production Electromagnetic Clutch assembly is not capable of offering the Third Position Hold feature, therefore, a new Electromagnetic Clutch design is needed to carry on the new and improved Power Liftgate model for the next generation of gate closure devices. The following thesis study is based upon design and improvements of the next generation GM-T900 Clutch assembly, capable of a Third Position Hold option, or in other word, a clutch mechanism with no indefinite engagement time limitations.

The thesis project will focus on the steps that are taken to design, test, and validate the functionality of the newly developed clutch mechanism.

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1.0 Background

Magna Closures has been the leader in design and manufacturing of Power Liftgates for the past decade. Power Liftgate mechanisms, designed for SUVs and Minivans, are a luxury item that could add comfort to the vehicle by offering automatic closure of the SUV gate or so called Trunk Lid. At present, companies such as Honda, Toyota, General Motors, and Chrysler are working toward the addition of luxury features to their vehicle designs, and the Power Liftgate is one of the features that could add more value to the vehicle from the consumer's point-of-view. In some cases, handicap drivers could see the Power Liftgate feature as a added value, and therefore, narrow down his or her car selection choices. Big automotive companies such as GM tend to see the luxury features as a key selling point, meaning these added items might help some buyers select their vehicle over hundreds of other competitor options.

After a decade of manufacturing Power Liftgates for Chrysler and General Motors, Magna Closures would like to offer a Closure Mechanism that is more than just a function to open and close a gate. Next to safety and durability, the comfort of the consumer is a key feature of the closure device, and it is important to think outside of the box and offer something that is new and has not yet been offered by competitors; that is, the Third Position Hold feature.

Imagine a customer with a short garage ceiling who has trouble opening and closing his or her SUV gate while inside. In this likely scenario, the gate may hit the ceiling and as a result, damage the vehicle. In this case, using the Power Liftgate is not a good idea, due to the fact that the Geared Motor Mechanism will lift the gate to the end of its reach, leaving the consumer with a potentially-damaged product. What, then, is the solution to this problem? Holding the gate with one hand, while removing one's parcels out of the trunk is both a hassle and unsafe, yet using the Powered Liftgate could result in vehicle and property damage. In the auto industry, it is important to consistently seek solutions to such functional problems. In this case, if the Powered Liftgate were capable of holding the gate at any angle or height desired as needed, for any length of time, the problem brought forth in this example would be solved. At present, one poses the question as to why the current GM-T900 Power Liftgate isn't capable of holding the gate at any intermediate angle. The answer lies at the foundation of the by Power Liftgate and the Liftgate mechanism as a system.

The gates of GM SUVs consist of four main components; the gate frame, the hinges, the latch, and the pair of gas-struts (Fig.1.1). The SUV gate is a heavy component, and in order to open and close the gate safely, a pair of gas-struts are added to the Liftgate mechanism. The gas-struts act as dampers, and by storing energy in the fluid, they create a counterforce balance in the system. Most of us have experienced the effects of the gas-struts on the vehicle gates. For instance, in the act of manually-opening the gate of an SUV or Minivan, the struts assist one in opening the gate smoothly and easily. In fact, at certain angles, these struts can open the gate without one's manual effort. During the closure, the mass of the gate assists the operator in the compression of the gas-struts.

The gas-struts play an important role in the operation of the Power Liftgate mechanisms. Without gas-struts, the Power Liftgate will not be able to operate the gate, and this shows that the system is designed to work with the gas-struts. Due to safety regulations, the design of the Power Liftgate must still operate even if one of the two gas-struts has failed. It is easy to see that why the Third Position Hold requires the clutch assembly to be engaged at all times. Depending on the hold position angle, the gas-struts will apply a load of pressure to the gate assembly, and upon the disengagement of the clutch assembly, the struts will open or close the gate. The idea is to keep the clutch engaged, and therefore the struts will not be able to change the position of the gate.

The question has arisen that if the motor is not running, would the struts not back-drive the gear train and slowly change the gate position? However, this is not an issue as the high input-over-output gear ratio of the gear motor assembly does not allow the mechanism to back drive the motor. Nevertheless, it is clear why the design of a new clutch assembly is required to convert the GM-T series Power Liftgate into a Third Position Hold capable mechanism.

Fig.1.1 **Buick Enclave Rear Trunk Gate**

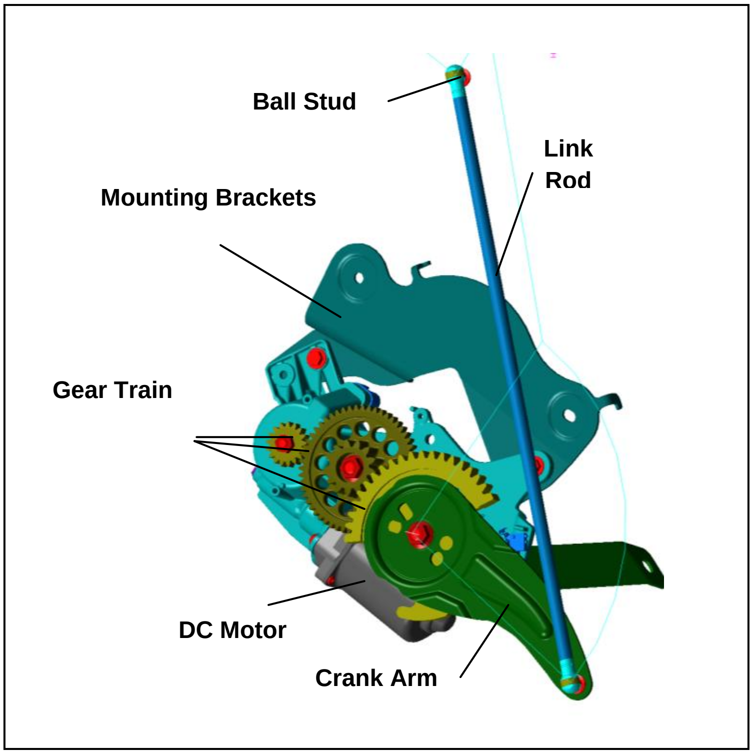


Fig.1.2 **GMT-900 Powered Liftgate Mechanism**

2.0 Objectives

The aim of this thesis study is to design a clutch assembly which is capable of being engaged and disengaged for long durations and without any time limitation, and therefore, offering the possibility of Third Position Hold function to the Power Liftgate.

The Third Position Hold option of the GM-T900 series Power Liftgates requires a new design of an Electromagnetic Clutch Mechanism. The current production Electromagnet Clutch Mechanism, used in the GM-T 900 series, cannot be engaged for a long duration, due simply to the rapidly rising temperature of the stator coils. The damaged stator assembly causes short circuit and failure of the clutch mechanism.

It is important that the clutch assembly is designed using the Electromagnetic Mechanism, since it is needed to control the clutch assembly using the existing electronic clutch control module. The EM Clutch assembly will be designed to be replaced with the current production EM Teeth Clutch, and therefore, no other assembly changes will be required on the GM-T 900 Power Liftgate series. The design of the clutch assembly requires complex analysis of electromagnetic and magnetic fields, and it is crucial to achieve reliable simulations in order for the prototype of the design to function as it is intended. The projected outcome of this thesis design study is the fabrication of a prototype model of the EM clutch mechanism which is used to validate the calculations nd the design of the product.

3.0 Motivation

Automotive industry has high demands for designing and manufacturing mechanisms and new technologies that can offer better functionalities, at higher durability and lower costs. In today's economy, it is proven that automotive industry needs to set path into a new era, and develop vehicles with greener and more economical plans. Therefore, as a mechanical engineer, identifying solutions for existing problems can guarantee successful path in terms of future career and experience.

The PEY (Professional Engineering Year) experience at Magna Closures had given the opportunity to identify one of these industrial problems and to take the challenge to demonstrate and prove the method that can be the solution to this problem.

The new EM Clutch design will be an improvement upon existing Electromagnetic Clutch Assemblies available in the industry. Clutch Assemblies are one of the crucial components that are used by most of the Industries such as the Transportation, Aerospace, military, manufacturing and many other industries. Therefore, the design of this clutch assembly can be useful and ideal for many industries that rely on conventional EM Clutch mechanisms.

As a Mechanical Engineering with less experience it is crucial to initiate a design process of a new mechanism and drive the product from papers to prototypes. Engineers are businessman who can identify need and offer solutions to existing problems, and the topic of following thesis had been a solution for an existing problem in industry.

As an industrial partner, Magna Closures has accepted the offer to work on newly designed and improved clutch assemblies that could be used with the current GM-T900 PLG series. In the end, it is power behind a solution to a need that has created successful designs in the history of mankind, and this is an experience for a young engineer to challenge himself and take the journey of a new design and have a story to tell for future engineers. The possibility of a patentable design has been one of the motivations to this thesis study.

4.0 Concept Design and Methodology

4.1 GM-T 900 Electromagnetic Clutch Mechanism

The design of the Third Position Hold EM clutch includes the combination of both permanent magnets and the electromagnets, used to achieve a new clutch mechanism.

Before delving into this concept, it is easier to first understand the overall design mechanism of the GM-T series, the EM Tooth Clutch. Figure 4.1 shows that the GM-T900 clutch assembly consists of two Serrated Torque Plates, the stator assembly, the separation spring, and the main clutch shaft. To engage this clutch mechanism, the current passed through the coiling solenoid of the stator assembly and as a result, an electromagnetic field is created. The magnetic flux passed through the top and bottom clutch plates creates a clamping force. The clamping force exerted in-between the two plates is dependent upon two variables; that is, the magnetic flux density (B), and the flatness of the two clutch plates. For a constant flux density, the higher the flatness tolerance on the surface of the two plates, the higher the clamping force will become. Good-machined surfaces will have less gaps and therefore less magnetic flux leakage. A good GM-T900 clutch assembly has about 1000N of static normal clamping forces, and this varies on each clutch assembly, due to existing tolerances.

The clamping force engages the top and bottom teeth plates and therefore the torque can be transferred through the wheel gear, to the clutch shaft. The separation spring is designed to separate the two plates once the magnetic flux is eliminated.

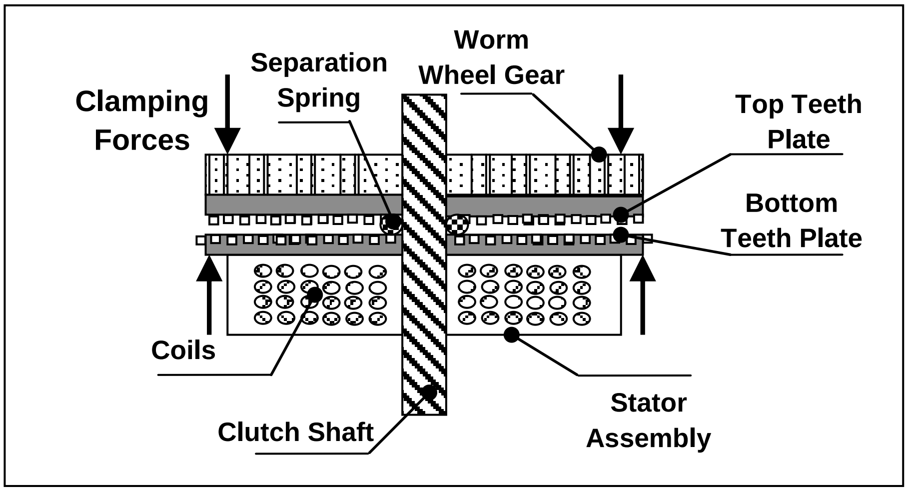


Fig.4.1 **Cross Section of the GM-T Series Electromagnetic Clutch Mechanism**

4.2 Electromagnetic-Permanent Magnet Clutch Design

In section 4.1, it was shown that the GM-T 900 clutch mechanism is simply relaying on the magnetic flux generated by the magnetic field of the stator assembly in order to transfer torque through clutch plates, Fig.4.1. As mentioned previously, due to the resistance of the coil, there is a great amount of current passing through the wiring, which is then converted into unwanted heat. The clutch mechanism does not contain any intended coolant flow; therefore, the clutch will not be able to be engaged for long durations. The insulation of the coil wire will melt, and this will cause short circuit and clutch failure. To design an EM clutch mechanism that could be engaged for long durations, and without being damaged, a new electromagnetic clutch with a combination of permanent magnets was proposed.

In this proposed design, the magnetic flux of the permanent magnet is used to engage the toothed torque transfer plates to the main rotor. Therefore, the torque is transferred through the shaft to the worm-wheel gear. It is important to observe and understand that the permanent magnet does consume any energy to keep the plate engaged. The residual magnetism, which acts as stored magnetic field energy, is the key idea of this design. To disengage the clutch plates, an electromagnetic field is generated by the stator. This in turn will weaken the magnetic field of the permanent magnet and will cause the release springs to push the clutch plates away from the effective magnetic field (Fig.4.2).

The question which presents itself is how to engage the clutch mechanism. Using reversed polarity of the stator coil, the direction of the magnetic field intensity of the coil, *H*, will be changed. As a result, the permanent magnet will be strengthened and the clutch plates will be attracted back to the ring permanent magnet. Once the clutch plates are back into the engaged position, the current passing through the coil can then be cut off, and the permanent magnet will keep the plates engaged while torque can be transferred through the clutch.

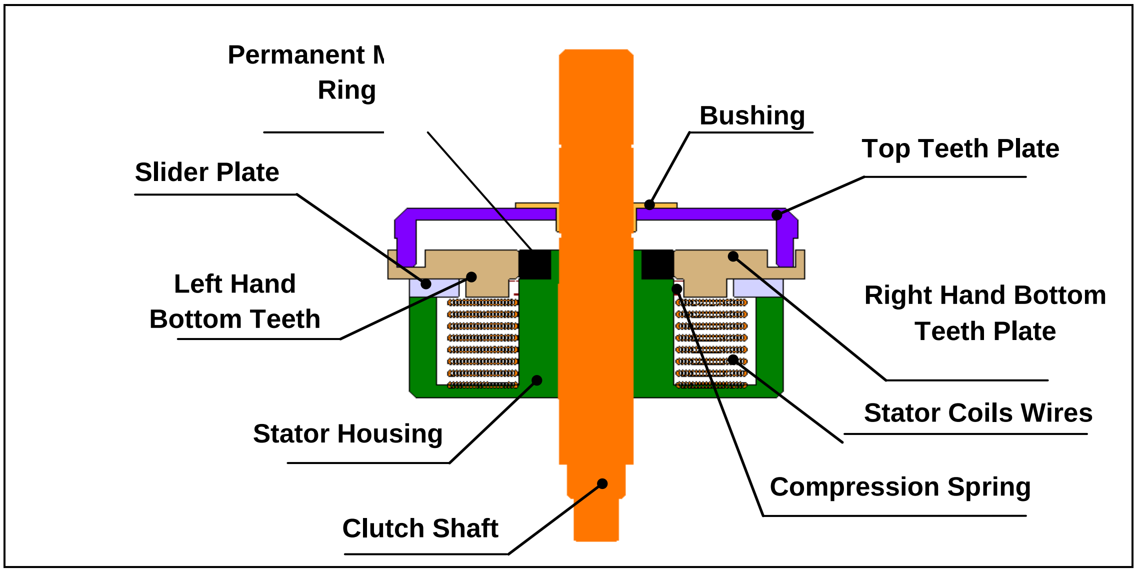


Fig.4.2 **Electromagnetic-Permanent Magnet Clutch Design Cross-Section**

4.2.1 Advantages and Disadvantage

The main advantage of the proposed mechanism is that the coil does not need constant current to keep the clutch engaged. It is important to note that to engage or disengage the clutch assembly, only short interval of supplied voltage to the coil is enough to engage or disengage the clutch, (Approximately time <0.5 sec). This results in an increased cycle-life of the part, and a more efficient clutch assembly. The current GM-T900 clutch assembly consumes around a rated of15 Joules of energy every second.

The main disadvantage of this design is the limited magnetic force that can be offered by permanent magnets. Therefore, it is important to select the right type of magnet with the correct magnetic flux density in order to be able to transfer the required torque. The following section shows the possible design solutions to these problems. One of the issues surrounding permanent magnet selection is the high cost of the magnets themselves.

5.0 Design Theory of the P-EM Clutch Assembly

5.1 Teeth Clutch Plates

The new clutch design uses the similar design mechanism used for the Drum Brake system of automotives braking system, Fig.5.1. The fiction pad or “Brake Shoes” are forced against the outer friction ring (i.e. rotor), using hydraulic force, therefore creating an opposite rotational torque on the wheels. Standard Drum Brake mechanisms use hydraulics in order to create the normal forces on the brake shoes; however, in the new clutch design, magnetic flux created by the magnetic field will supply the normal clamping force.

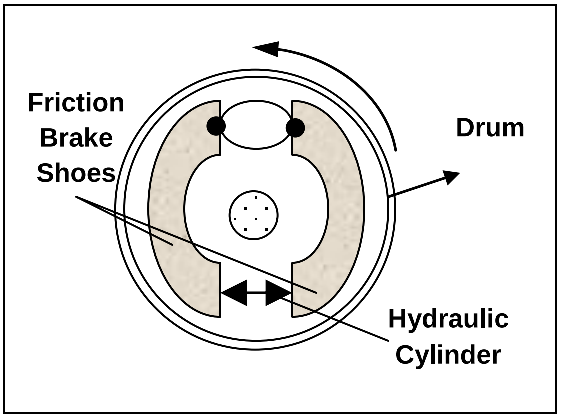


Fig.5.1 **Vehicle Drum Brake System**

The problem with such design is that the permanent magnet will not be able to supply enough normal clamping force for the required torque transfer (30 Nm).

To solve this issue, serration clutch plate design was purposed, and part of the design process of this clutch includes designing the teeth profile that could offer decent torque transfer.

5.2 Stator Mechanism

The magnetic field of the ring permanent magnet located in the centre of the clutch assembly (Figure 5.2), attracts the left and right bottom clutch plates. Due to the design characteristic of this mechanism, the serrations of the bottom clutch plates will engage with the serrations of the top clutch plate. Therefore, the stator, which is constrained to the clutch shaft using knurls, will be able to transfer torque to the worm wheel gear which is mounted onto the top clutch plate (Not shown in Figure). Now the clutch is engaged and the torque can be transferred through the motor to the gear train. Here, the opposing magnetic field intensity created in the presence of the ring magnet will be capable of reducing the magnetic flux density of the permanent magnet to near zero. This effect is known as “Magnetic Coercivity”, and will be discussed in section 5.3. The compression springs located in-between the slider plate and the bottom plates will be able to overcome the force of the magnetic field and slide the plates away from the effective magnetic field. Due to the special characteristic of permanent magnets, the magnetic flux density of the ring magnet will be back to its original strength once the electromagnetic field is deactivated. The external electromagnetic field is generated by the coil that is placed inside of the stator assembly (Figure 5.2.). At this point, the bottom clutch plates are outside of the effective magnetic field of the magnet, and as a result, the magnet cannot attract the plates back into the engaged position.

In order to activate the clutch assembly, a similar electromagnetic field will be generated by the stator coil; however, an opposite polarity is required to create the specific direction of the magnetic field lines. At this point, it is wished to strengthen the magnetic field and help the ring magnet to overcome the spring forces and engage the clutch assembly. Once the clutch plates are engaged, the electromagnetic field can be disconnected. Since the plates are inside the effective magnetic field area, the clutch will engage.

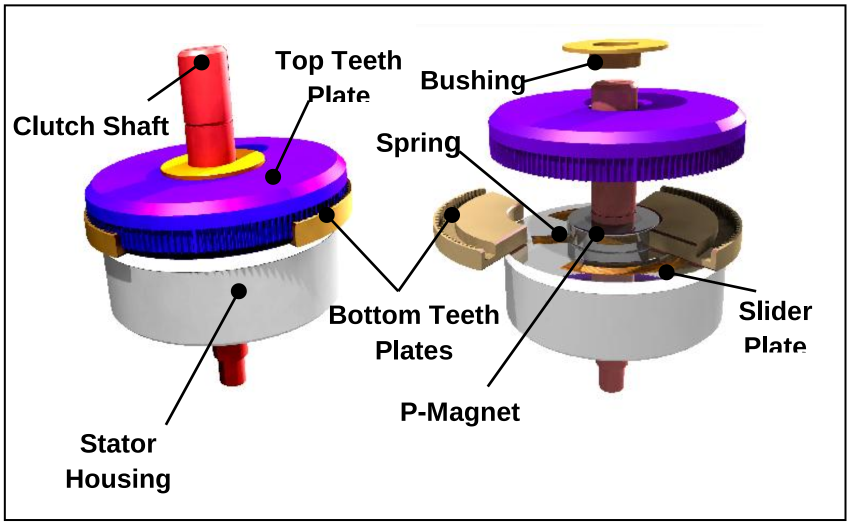


Fig.5.2 **Electromagnetic – Permanent Magnet Clutch Design**

5.3 Permanent Magnet

This section will focus upon the property and structure of magnetic materials. In order to design the EM Clutch, it is important to understand how permanent magnets are classified. Using this notion, the proper type and strength of permanent magnet will be selected, (See section 6.1).

In the industry, the permanent magnets are classified as materials that have high material permeability and magnetization susceptibility, [1]. In order to understand the two properties of magnets, it is important to introduce the hysteresis H-B curve. The H-B curve refers to the graph of Magnetic Field Intensity (H), verses Magnetic Flux Density (B). A current running through a piece of wire can create a magnetic field circling around the wire, and this magnetic field is called the Magnetic Field Intensity, (A/m),[1]. The

Magnetic Flux Density is simply the density of Magnetic Flux lines (Φ), which are induced from the north pole of the magnetic field to the opposite side of the magnetic field, or the South Pole.

The Magnetic Flux has the unit of Weber (Wb), [1].

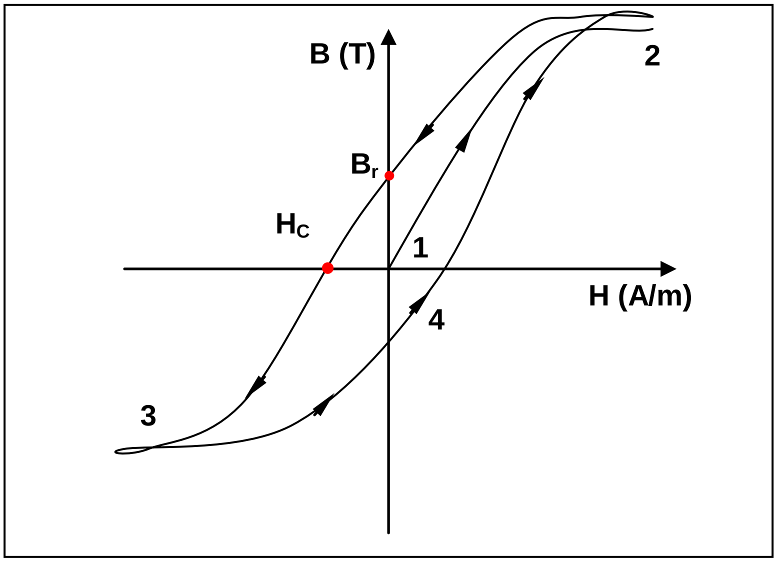


Fig.5.3 **B-H Curve Hysteresis Curve of a Magnetic Material**

As shown in Fig.5.3, an increase of magnetic field intensity can increase the Magnetic Flux Density, B, up to the saturation limit, (Point 2). When the material is saturated, the effects of magnetic field on the magnetic flux density is reduced, meaning all of the magnetic domain partials are aligned and material has reached its maximum magnetic flux density.

As the external magnetic field decreases, the material will slowly lose the magnetic flux density. However, depending upon the material properties such as magnetic permeability (μ) and material susceptibility (*X*), the magnetic flux density may not return to zero. This is due to the hysteresis effect of the magnetic material. During the magnetization period, some of the magnetic field energy will be converted into heat. Therefore, after the reduction of magnetic field, not all of the magnetic domain of the material will be able to move to the original-disaligned position [1].

On the hysteresis curve (Fig.5.3), non-zero residual magnetic flux is shown as “Br”. This effect is seen in permanent magnet materials and it is called “Magnetic Remanence”. Magnetic Remanence is the level of magnetic flux density left inside of the material during the magnetization procedure. In other words, the higher the Remanence, the stronger the permanent magnet will be [2].

Another property of permanent magnetism is the *Magnetic Coercivity*, which is defined by the amount of Magnetic Field (H_c) required to reduce the Magnetic Flux Density, (Br) to zero,[2] (Fig.5.3). This concept is used to reduce the magnetic flux density of the permanent magnet and therefore to disengaged the clutch mechanism. The Magnetic Field Coercivity will be applied using the solenoid coil, and therefore, correct calculation on the solenoid coil is essential to this design.

Using the hysteresis curve of a magnetic material, the product of maximum magnetic intensity (H_{max}), and maximum magnetic flux (B_{max}), is applied to calculate the maximum energy density of the permanent magnet,($B\ H_{max}$).

This value corresponds to the size of the magnet that is needed for a certain amount of magnetic energy. Therefore, the higher the BH_{max} , the smaller the selected permanent magnet needs to be .

These properties are very useful and they play important roles in the selection of the correct type of permanent magnet. Using the right combination of Magnetic Remanence, Magnetic Coercivity, and Magnetic Energy Density, one could design the clutch and the electromagnetic field to function in the intended way. At this point, it is clear that there are many factors that need to be considered in the selection of the right materials and the design of the stator assembly.

5.3.1 Magnetization of Permanent Magnets

The grain structure of the magnetic material has a certain ordered magnetic domain which creates a medium source of magnetic field flux which is called the Magnetization Vector, M [1]. Using mathematical formulas, the total magnetic field of the magnetic material can be demonstrated into the following order:

$$\Delta\times(\frac{B}{\mu_o}) = \Delta\times H + \Delta\times M \rightarrow B = \mu_o(H+M) \qquad [\mathrm{T}] \qquad \text{Eq.5.1}$$

It is important to know that the Magnetization value in free space is zero, [2].

Using the Magnetization vector, we can introduce another property of magnetized material called Magnetic Susceptibility, ***X*** [1]. Magnetic Susceptibility is a measure of how easily the material could become magnetized if it is introduced into an external magnetic field.

Therefore, substitute X into Eq.5.1:

$$B = \mu_o(1+\chi_m)\,\mathrm{H} = \mu H \qquad [\mathrm{T}] \qquad \text{Eq.5.2}$$

$$B = \mu_o\ \mu_r\mathrm{H} \qquad [\mathrm{T}] \qquad \text{Eq.5.3}$$

Using both Eq.5.2 and Eq.5.3, we can drive the relative permeability:

$$\mu_r = (1+\chi_{\mathrm{m}}) = \frac{\mu}{\mu_o} \qquad [N/A^2]$$

5.4 Electromagnetic Field (Magneto-Static)

H and B Curve

This section will introduce the basic theory of the electromagnetic field. The electromagnetic field design of the clutch assembly is based on static analysis of the field. This means that it is assumed there are no changes in the applied voltage and current of the magnetic coil during the theoretical analysis of the magnetic field.

In the previous section, the Magnetic Field Intensity (H), and the Magnetic Flux density (B) were introduced. However, there is simple relation between the H and B. Material permeability is a property of any material which is used to identify the magnetic field conductivity or resistivity of materials. Air has very low magnetic permeability and on the contrary, iron has high permeability.

$$B = \mu H \qquad [\mathrm{T}] \qquad \text{Eq.5.4}$$

$$\mu_o = 4\pi \times 10^{-7} [N/A^2]$$ Permeability of Free Space (Air)

Material permeability is a property that is found in metals, ceramics and even gases; however, ferromagnetic materials tend to have higher permeability compared to other non-ferrous materials [1].

Experimental values have shown that materials with high permeability values ($\mu >> \mu_o$) do not follow equation 5.4, [1]. This is due to the hysteresis and the residual magnetism that is seen in ferromagnetic materials (See Section 5.3).

$$B \neq \mu H \quad [\mathrm{T}] \quad (\mu >> \mu o)$$ Eq.5.5

One of the basic theories of the electromagnetic field is that the current flowing through a wire will create a magnetic field around the wire. Here, the right hand rule is used to identify the direction of the magnetic flux and the magnetic force. This is known as the “Ampere’s Magnetic Force” theory. The thumb is pointed into the direction of the flowing current, the curved fingers point into the direction the magnetic flux, and the force of the magnetic field is perpendicular to current, I, and the magnetic flux density, B (Fig.5.6).

$$F = \mathrm{I} \times \mathrm{B}$$ Eq.5.6

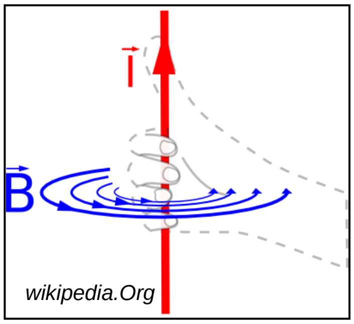


Fig.5.4 **Right Hand Rule**

The relation between the Magnetic Field Intensity, H, and current, I, is:

$$\oint_C H.dl = I \quad [\mathrm{A/m}]$$ Eq.5.7

The close loop integral is used to calculate the Magnetic Field strength around the centre of a wire that is carrying current.

5.5 Line of Magnetic Flux

It is known that magnetic flux lines have direction, and for magnetic dipole materials, the lines travel from the North Pole into the South Pole, closing the loop (Fig.5.5) [1]. This concept can be used to drive the following equation, Eq.5.8:

$$\oint_s B.dS = 0 \quad \text{(For Closed Surfaces)} \qquad \text{Eq.5.8}$$

This equation shows that the total magnetic flux, *Φ*, of the surface of a magnetic material or electromagnetic material, is simply zero [1]. This means that the magnetic field must have equal number of flux lines leaving and equal number of flux lines entering the surface of the material [1]. For non-closed surfaces, (open surface), the magnetic flux of the surface is defined using the following formula (Eq.5.9) [1].

$$\oint_s B.dS = \phi \quad \text{(For Closed Surfaces)} \qquad [\text{Wb or T.m}^2 \text{ or N.m/A}] \qquad \text{Eq.5.9}$$

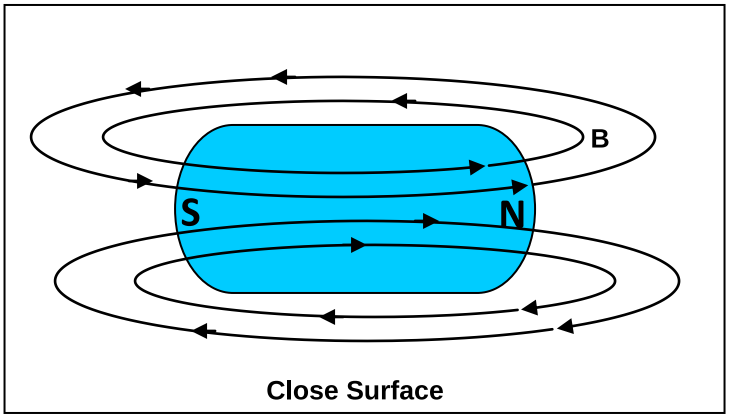


Fig.5.5 **Closed Surface Flux Lines of the Magnetic Field**

6.0 Design Specifications

6.1 Design Assumptions

The following electromagnetic field assumptions are made based on theoretical assumptions needed in calculations and simulations of the Electromagnetic Field System.

1- The calculations are done based on Steady State conditions.
2- Static conditions are assumed. This means no variation in voltage, current, material properties, and temperatures.
3- The calculations and simulations are conducted assuming the ambient temperature of 25 Degree Celsius.
4- The permeability of Free Space, or Air is $\mu_o = 4\pi \times 10^{-7} [N / A^2]$
5- The permittivity of Free Space, or Air or Vacuum is $\varepsilon_o = 8.85 \times 10^{-12} [C^2 / Nm^2]$
6- Relative Permeability of Air is 1.
7- All the computer simulations of the parts are simulated in free space, as the boundary conditions of the space.
8- Nonlinear relationship of $B \neq \mu H$ exists for ferromagnetic materials. $(\mu >> \mu o)$
9- Linear relationship of $B = \mu H$ exists for material with relatively smaller permeability.
10- Relative Permeability of Air is 1.
11- All of the touching surfaces of the clutch are precisely machined and there are not magnetic flux leakages.

6.2 Design Specifications

To design the P-EM Clutch, the following lists of specifications are provided:

1. Design for Maximum torque transfer of 30 N.m
2. Design to operate for voltage of 12 Volts-DC

(Note: The design of the clutch for General Motor Voltage range specification of 9-16 Volts is out of the scope of this design study).

3. Design for operation temperature of 25 Degree Celsius.

(Note: The study of temperature variations and tolerances (GD&T) are not within the scope of this thesis study).

4. Design for strength and durability (One Life Cycle or 10’000 Cycles)
5. Design with the actual packaging dimensions of the GM-T900 Clutch assembly in order to replace the New EM-P Clutch Design with the current production EM Clutch
6. Design of this clutch assembly could withstand non-limited engaged durations.
7. The design of this clutch assembly could withstand non-limited disengaged durations.
8. The design of the P-EN clutch assembly must be designed for possibility of mass production manufacturing and ease of assembly in mind.
9. The design of the P-EM clutch assembly should not relay on hard to manufacture tolerance stacks, in order to keep the cost down.

7.0 Detail Design Analysis and Calculations

7.1 Permanent Magnet Design

The permanent magnet used in this design, is a critical piece of the assembly that is needed to be designed and selected with all the criteria in mind. The science of engineered permanent magnets has allowed us to select few choices for our design, such as Neodymium Permanent Magnets, Samarium Cobalt Permanent magnets, and Ceramic Permanent Magnets. Each of these magnetic materials is possible to be fabricated into the specified dimensions, however, with the limited prototype quantities the cost of the magnets will be high and over the budget of this project. Therefore, for the purpose of this thesis study, it was decided to select the best possible magnetic material that is suitable in terms of design calculations and affordability. The design of EM-P clutch mechanism will be based on the selected magnet.

Neodymium	Br [Gauss or Wb/m2]	Br @ 0.05" distance from the Surface [Gauss or Wb/m2]	Hc [Oersted or A/m]	Prototype Cost (25mmOD-15mm ID)
35	**12300 / 1.23**	**3518/ 0.3518**	**11300/8.98x10^{5}**	**$15/Ring**
42H	**13300/ 1.33**	**3810/0.3810**	**12800/1.01x10^{6}**	**$25/Ring**

Source: K&J Magnetics (minimum order of $200)

Table.7.1 **Neodymium Rare Earth Permanent Magnets**

The search for magnetic material had left the selection with two options, Neyo. 35, and Neyo. 42H. Table 7.1shows the magnetic characteristics of the two magnets, including the prototyping costs. It is clear that Neodymium 42H offers a higher magnetic flux density, (1.33 T), however, it is more expensive than the Neodymium 35.

The Br ,or *Magnetic Remanence*, represents the maximum magnetic flux density created by the permanent magnet only, right after magnetization process(H=0). The Hc, or *Magnetic Coercivity*, represents the magnetic field intensity or in other word, the magnetic field required to reduce minimize the magnetic flux density of the permanent magnet to zero (B=0), Fig.4.5. These two terms are very critical in the design process of this clutch, and the functionality of the assembly lies on these two qualities of the Neodymium 35 and 42H Magnets.

Neodymium is part of the Rare- Earth Permanent Magnet group that has high strength to size ratio. This magnet is ideal for the design of this clutch assembly due to high magnetic flux density offered by this magnet. However, the high costs of the Neodymium material, ($Nd_2Fe_{14}B$), is one of the downsides of this magnetic material. Fig. 7.1 .

http://en.wikipedia.org/wiki/Neodymium

Fig.7.1 **Neodymium Element**

For the purpose of this project, the Neodymium 35 will be used to fabricate the prototype assembly of the EM-P clutch mechanism. The Neodymium 35 will be magnetized diametrically, meaning the North Pole will be on one half of the outer ring and the South Pole will lie on the other half, and the magnetic field will be perpendicular to the axis of the ring, (figure 7.2)

7.2 Permanent Magnet Clamping Force

The goal is to calculate the effective distance of the magnetic field of the permanent magnet relative to the bottom clutch plates. This is crucial to the calculations, and is needed to design the bottom clutch plates, the slider plate, and the two compression springs.

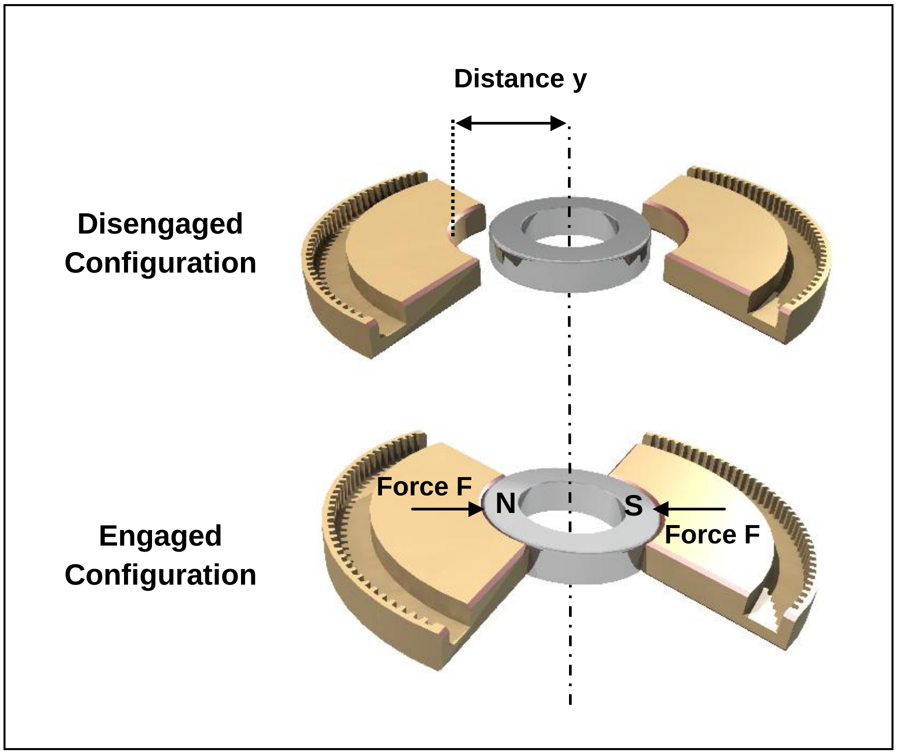


Fig.7.2 **Engaged & Disengaged Configuration of Bottom Clutch Plates in the Active/Inactive Ring Magnetic Field**

In order to achieve the required torque transfer, the permanent magnet must be designed to attain the needed normal clamping force on the surfaces of the bottom plates.

This section will introduce the basic formulas that are used to calculate the clamping force and the effective magnetic field of the permanent magnet.

In order to calculate the magnetic field force applied on the bottom clutch plates, it is possible to use the following equation to approximate the clamping force. The value of the magnetic flux Remanence, Br, will be used to calculate the clamping force applied on ferromagnetic steel (Fig. 7.2). One of the assumptions made in section 6.0 implies that the surface of the magnet and the clutch plates are both machined and good surface finish is applied on both pieces. It is crucial to remember that magnetic flux leakage in between the plate and magnet can cause a surprising drop in the value of the clamping force.

$$F_{clamping}[N] = \left(0.58 B_r^2 t\sqrt{A}\right)_{[lbf]} \qquad \textbf{Eq.7.1}$$

Br=12.3 [Kilogauss], Magnetic Flux Remanence

t= 0.005 [m] or 0.1968 [in], Thickness of the Ring-Magnet

A=1.33x10^{-4} [m^2] or 0.2061 [in^2] Surface contact area of the clutch plate and the magnet (See Fig.6.4)

Sample Calculation

$$F_{clamping}[N] = \left(0.58 B_r^2 t\sqrt{A}\right)_{[lbf]} = \left(0.58 \times 12.3^2_{[\mathrm{Kilogauss}]} \times 0.1968_{[in]} \times \sqrt{0.2061}_{[in^2]}\right)_{[lbf]} \times \left[\frac{4.448_{[N]}}{1_{[lbf]}}\right] = 34.87[\mathrm{N}]$$

7.2 .1 Effective Distance of the Magnetic Flux

To keep the clutch plates into disengaged position, once the clutch assembly is disengaged, the assembly must be designed with specific dimensions so that the plates are placed away from the effective magnetic field area. As the plates are moved away from the centre of the permanent magnet ring there will be reduction of the flux density. This phenomenon is well known due to the effect of permeability of the air, or in other word, the air acts as high resistive material which acts as magnetic field insulator, [2].

The equation 7.2, will be used to determine the magnetic flux density of the ring magnet of Neodymium 35, moving away from the surface of the permanent magnet, (either North or South Pole surfaces) along the directional line of Y, (Figure. 7.3), [6].

B_y represents the magnetic flux of the magnetic ring along line Y and graph 7.2 is used to show the reduction in magnetic field density of the permanent magnet, from the surface of the ring.

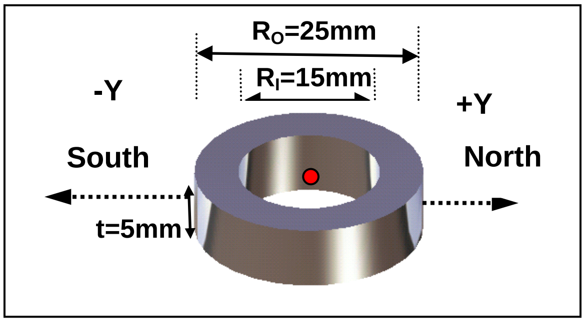
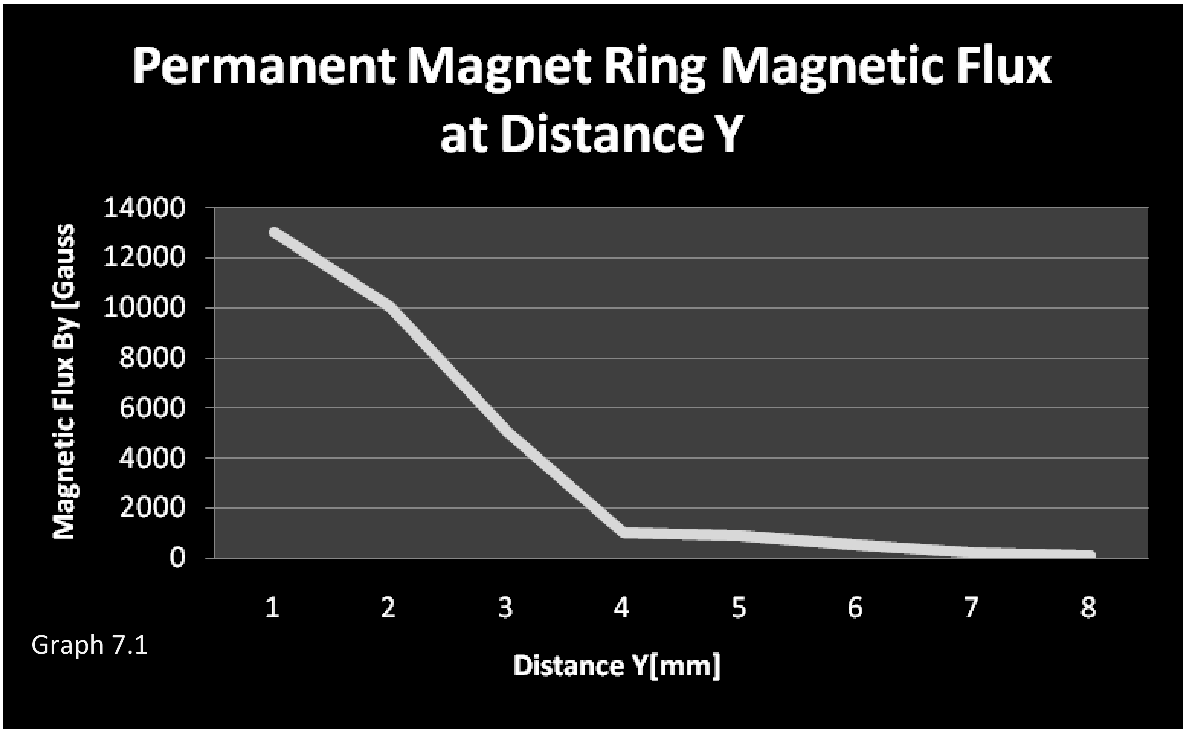


Fig. 7.3 **Ring Permanent Magnet**

-Note in this equation, B_r, (1.23 T), represents the magnetic Remanence of the permanent magnet Neodymium 35.

$$B_Y = \left(\frac{Br}{2}\right)\left[\left(\left(\frac{t+Y}{\sqrt{RO^2+\left(+Y\right)^2}}\right)-\left(\frac{t+Y}{\sqrt{RI^2+\left(+Y\right)^2}}\right)\right)-\left(\left(\frac{Y}{\sqrt{RO^2+Y^2}}\right)-\left(\frac{Y}{\sqrt{RI^2+Y^2}}\right)\right)\right] \qquad \text{Eq.7.2}$$



Graph 7.1

The graph shows that there is a major reduction in the magnetic flux of the permanent magnet, and this is due to the air gap. At distance 1mm away from the surface of the ring, the forces exerted upon the clutch plates are about 0.29 N (Eq. 7.2). These results will be used to design or select the proper spring, needed to move the plates away from the **effective zone**, **(Y>3.5mm)** to disengage.

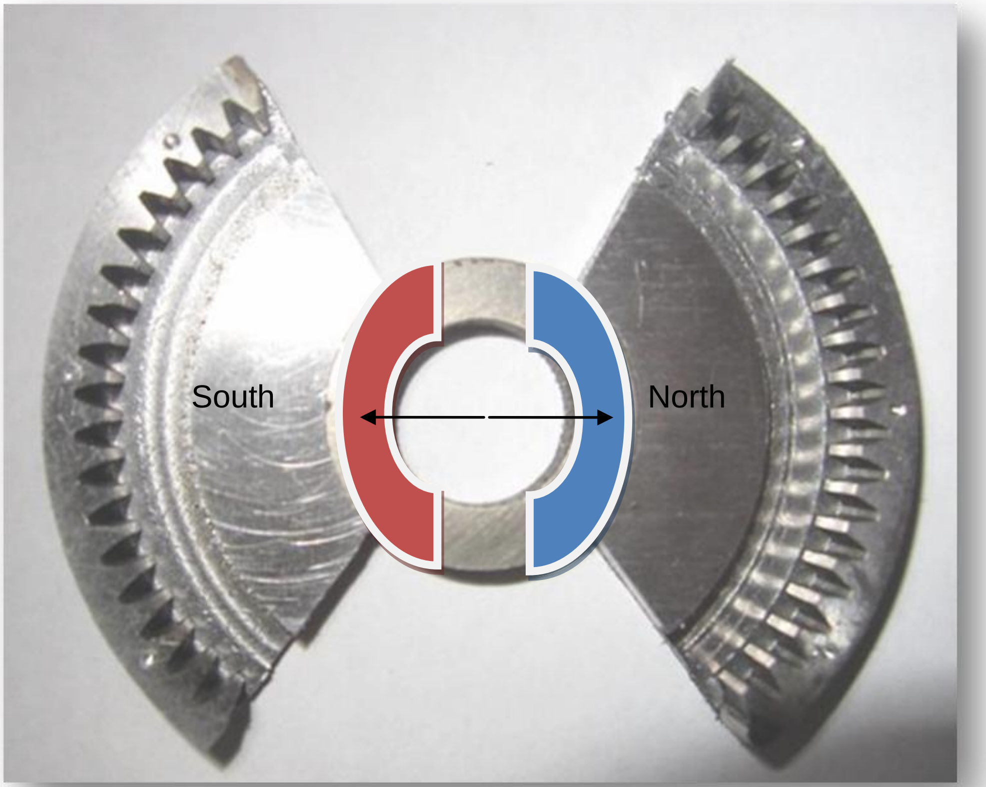


Fig.7.3.1 **Diametrically Magnetized Neyo 35 Ring Magnet Prototype and two left and right Bottom Plates**

7.3 Design of Stator Subassembly

The stator assembly is used to weaken and strengthen the magnetic flux density of the permanent magnet by applying counter direction current into the stator coil. This means the stator is responsible to disengage and engage the clutch assembly.

To disengage the clutch plates, the stator assembly will be designed in a way that it is able to reduce the magnetic flux density of the permanent magnet so that the springs will be able to overcome the clamping force of the permanent magnet, and therefore, the plates will be moved away from the effective area.

7.3.1 Stator Coil Design and Material Selection

-Source of Magnetic Potential or so called Magnetomotive Force, [1],

$$\mathcal{F} = NI = \int_0^l Hdl = \int_0^l \frac{B}{\mu} dl$$ Eq.7.3.1

-Calculate the Magnetic Field Intensity and Magnetic Flux Density of Solenoid, [1], Fig.6.1

$$NI = \frac{B}{\mu} l \Big]_0^l \rightarrow NI = \frac{B}{\mu} l = NI$$ Eq.7.3.2

$$B = \frac{\mu_o \mu_r N}{l} I \qquad [T]$$ Eq.7.3.3

$$H = \frac{N}{l} I \qquad [A/m]$$ Eq.7.3.4

$$\phi = B.S \qquad [Wb]$$ Eq.7.3.5

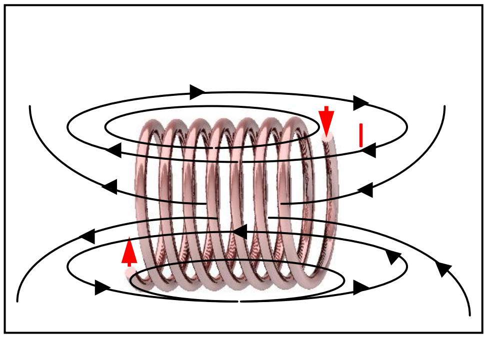


Fig.7.4 **Solenoid Coil Design for the Stator**

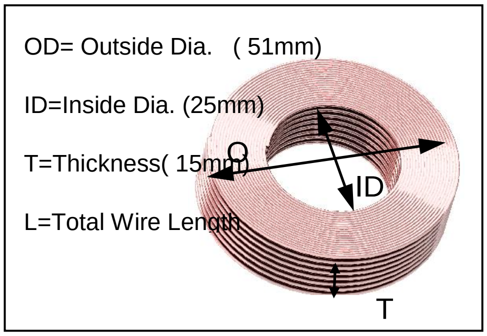


Fig.7.5 **The actual Stator Coil Dimensions**

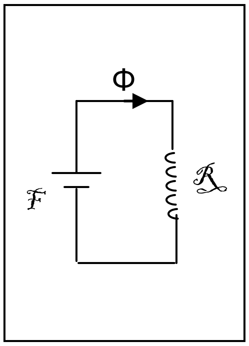


Fig.7.6 **Circuit Equivalent**

The Equation 7.3.4 suggests that the magnetic field intensity generated by the coil will heavily depend on the number of coil-loop turns, (N), and the current passing through the stator coil. It is noted that the limited housing dimensions, (Figure 7.5), will only allow for certain number of coil-loop turns depending on the selected wire gage, (Table 7.1). The wires are copper wire, sized with American Wire Gage or AWG standards. The following table, (Table 7.1), demonstrates the overall wire resistance of the stator coil using different wire size. Using the 12 volt battery as the average source of power from the vehicle power supply, will only allow for certain electrical current to pass through the coil. Nevertheless, the magnetic field generated by the coil will depend on this current, and the bigger wire size will offer higher current draw, but less number of coil-loop turns. The following graph, (graph 7.2), demonstrates the relationship between the coil wire gauge and the magnetic flux density generated by the stator assembly.

	Wire Size [AWG]	Outside Dia. [mm]	Wire Resistance [ohm/m]	N (Number of Coil Turns)	Total Length of the wire [m]	Total Coil Resistance [Ohm]	Current [AMP]
Suitable Wire Range	24	0.51	0.084	750	120	10.11	1.18
	25	0.45	0.106	943	151	16.05	0.74
	26	0.40	0.134	1196	192	25.64	0.46
	27	0.36	0.169	1499	240	40.55	0.29
	28	0.32	0.213	1904	305	64.93	0.18
	29	0.29	0.268	2367	379	101.79	0.11
	30	0.25	0.338	3023	484	163.92	0.07

Table 7.2 **Calculations for Several Copper Coil Wire Sizes**

Methodology

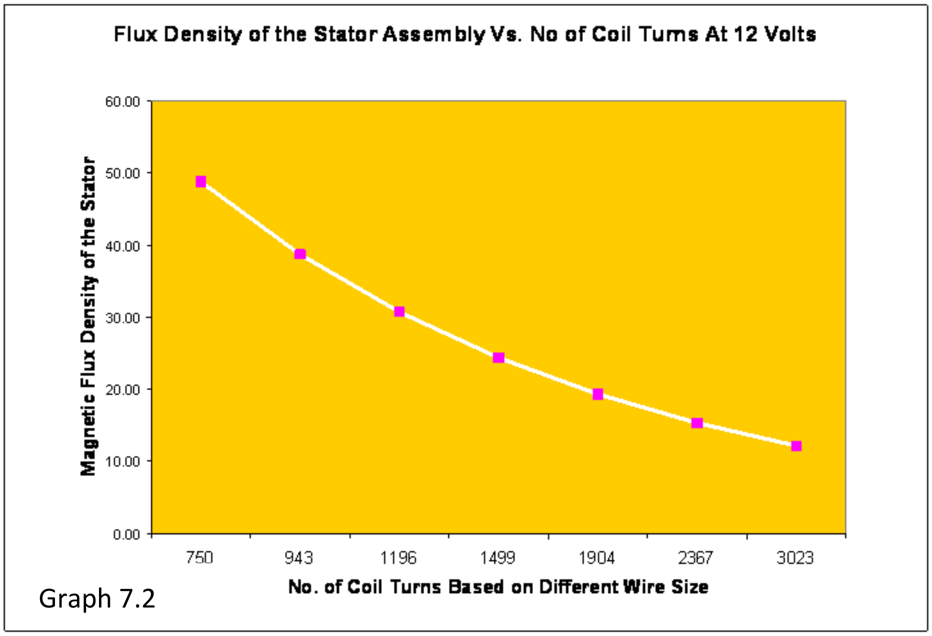
To approximate the total wire length ,L, used in the coil, depending on the number of wire turns and the wire size used in the coil

$$\text{Number of Wire Turns (Using the Coil Cross - Sectional Area)}$$
$$T \times ((OD - ID)/2)/Wi^2 = 15mm \times 13/0.510^2 = 749.71 or 749$$

This means there is approximately a maximum of 749 wire turns that can be made by a 24 Gauge wire. Table 6.1 shows the number of different wire gauges that could be used for the wire design.

Coil Wire Size Selection

Based on the graph 7.2, the 24 AWG wire will produce higher magnetic field intensity, and therefore, as a result, it will have a better counter effect on the magnetic flux density of the permanent magnet. As it is mentioned above, the goal is to design a stator assembly that can reduce the magnetic flux density of the permanent magnet so that the designed springs can disengage the plates. Since the springs create a negative counter force against the clamping force of the permanent magnet, during the engagement time, it is desired to design springs with minimum possible strength. Therefore, selection of the 24 AWG wire will be the best for the performance and success of this clutch assembly, (figure 7.7).



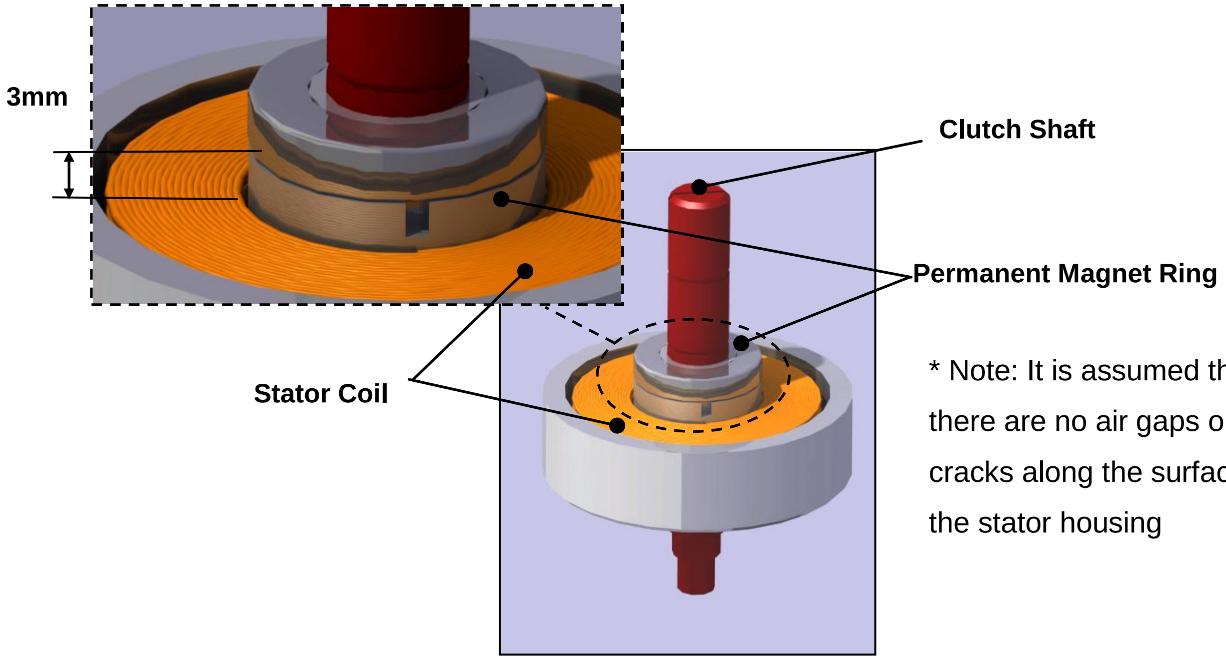
Graph 7.2

Fig.7.7 **24 AWG Coil Wrapping Jig**

7.3.2 Stator Housing Design

The coil is placed inside of low carbon steel core housing, and therefore stator generates higher magnetic flux density. The steel core will act as a conductor of the magnetic field, and high material permeability of low carbon steel alloy, (μr= 8.79E-03 N/A^{2}), will allow for higher magnetic flux density.

The magnetic field generated by the coil which travels along the surface of the stator housing, therefore creating a magnetic flux.



* Note: It is assumed that there are no air gaps or cracks along the surface of the stator housing

Fig. 7.7

Stator Assembly

Methodology

The permanent magnet ring is assembled on top of the stator core, which is located $3_{[mm]}$ on top of the stator coil assembly, (Figure 7.8). The stator coil calculations using the Equation 7.3.4 under the 12 volt voltage supply resulted into theoretical magnetic flux density of 48.8 Tesla.

Using the magnetic flux density of the electromagnetic field, it is possible to approximate the magnetic flux of the electromagnetic field around the permanent magnet ring, which is located 3mm away from the stator assembly,(Eq.7.3.6), [6].

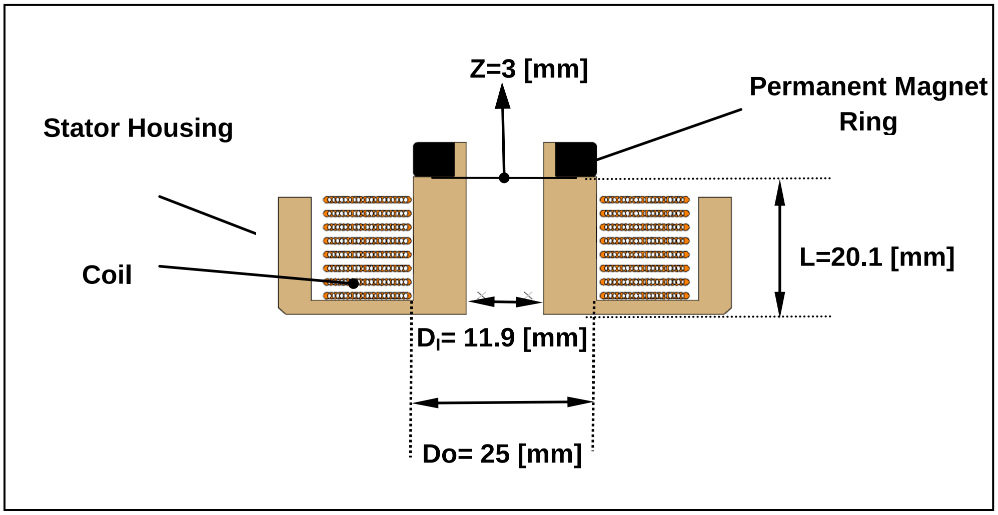


Fig. 7.8 **Cross-Section of the Stator Assembly Design**

$$B_Z = \left(\frac{Br}{2}\right)\left[\left(\left(\frac{t+Z}{\sqrt{R_O{}^2 + (t+Z)^2}}\right) - \left(\frac{t+Z}{\sqrt{R_I{}^2 + (t+Z)^2}}\right)\right) - \left(\left(\frac{Z}{\sqrt{R_O{}^2 + Z^2}}\right) - \left(\frac{Z}{\sqrt{R_I{}^2 + Z^2}}\right)\right)\right] \quad \text{Eq.7.3.6}$$

Therefore, the approximate magnetic flux at 3 $_{[mm]}$ away from the surface of the steel core cylinder, (assumed as a cylindrical core), is 1.13 Tesla. Depending on the direction of the flowing current through the coil, the North and South polarities of the electromagnetic field in relative with the permanent magnet field polarities can be assumed as added onto the magnetic flux of the permanent magnet or subtracted, as the total of magnetic flux density of the system, (B $_{total}$).

7.3.2.1 Disengagement Process

The simplified theoretical calculations demonstrate that the total magnetic flux density of the system will be reduced into 0.1 [Tesla], during the disengagement process of the clutch assembly. Equation 3.7 will be used to calculate the magnetic forces which are exerted upon the clutch plates, during this process. This value is crucial in designing the extension springs required for placing the clutch plates away from the effective-magnetic field zone, (See Section 7.2.1).

Weakened Total Magnetic Flux Density

$B_{Total\ [Tesla]} = 1.23_{\text{Ring Magnet}} - 1.13_{\text{Electromagnet}} = 0.10$ [Tesla] or 1000 [Gauss]

B *Total* **=**1.0 [Kilogauss]

t= 0.005 [m] or 0.1968 [in], Thickness of the Ring-Magnet

A=$1.33\text{x}10^{-4}$ [m^2] or 0.2061 [in^2] Surface contact area of the clutch plate and the magnet (See Fig.6.4)

Sample Calculation

$$F_{clamping}[N] = 0.58 B_r{}^2 t\sqrt{A}\ _{[lbf]} = 0.2304\ [\text{N}]$$

7.3.2.2 Engagement Process

Strengthened Magnetic Flux Density

$B\mathit{Total}_{\text{[Tesla]}} = 1.23_{\text{Ring Magnet}} + 1.13_{\text{Electromagnet}} = 2.36$ [Tesla]

7.4 Spring Design

Each clutch plate will be attached to an extension springs, which is mounted in between the clutch plate and the slider plates, (figure 7.9., and 9.6). The spring needs to be able to disengage the plates from the surface of the permanent magnet ring, once the magnet has weakened, and move it away from the effective-magnetic field zone. Therefore, the minimum required force to disengage the plates from the permanent magnet, and the distance that the bottom plates need to travel to be moved away from the effective zone are used in the design process of the extension spring, (figure 7.9., and 9.6)

Design Methodology

The theoretical calculations of the disengagement force ($F>0.23$[N]) and the non-effective magnetic field distance ($Y>3.5$ [mm]) are used to design the extension springs needed for the clutch plates to disengage.

Due to possibility of errors in estimates, the spring force of **5 [N]** will be required to disengage the plates. The theoretical weakened permanent magnet force indicates that to remove the plates during the disengagement process, a force of 0.23 [N] is needed to dislocate the plates; however, it is possible that the estimate value is quiet small and therefore higher magnetic field forces can be expected during the disengagement process. The maximum of 5 [N] is allowed to be used in the design of the P-EM clutch assembly. Nevertheless, it is crucial to keep in mind that higher spring force will result into subtraction from the permanent magnet clamping forces that keep the clutch mechanism engaged, therefore, experiments must be conducted to validate these theoretical values, and reduction in spring forces will result into higher torque transfer capacity for the clutch assembly.

The extension springs will need to move the clutch plates away from the permanent magnet, and the theoretical calculations indicate the any distance higher than 3.5 [mm] will be enough to keep the clutch plates from re-engaging. Due to possibility of error in the estimated theoretical value, it is decided to use **4 [mm]** as the traveling distance or the dislocation distance of the extension springs.

7.4.1 Extension Spring Characteristic

The data and information, gathered through the computer CAD model and the theoretical calculations of the clutch functionality, suggested that to look and identify possible extension springs that follow the required specifications and match the physical dimension that are required. Nevertheless, it is more accurate to use costume made springs to verify the design of the clutch assembly, however, the limited budget does not allow this method. It is important to understand, the following selected spring was the best possible choice, after much considerations.

Spring out sourcing Part Number 80020

Manufacturer Century Springs

Fig.7.9 **Spring PN 80020**

Initial Force

The initial force of the extension spring is very important, and this is due to the distance between the plates and the permanent magnet results into lower clamping force, and therefore, it is required to keep the initial tension of the spring, as low as possible, (less than 0.5 N). The initial spring is defined by the material, the spring index, and material stress-relieving processes, [7].

Spring Ends

The both ends of the extension spring is designed as a twist loop or so called Hook, (Figure.7.9 and 7.10). The spring connection pins, (Figure 7.10), have diameter of 1.0 mm, and therefore the spring is designed with internal diameter of 1.3mm.

Design Material and Spring Constant

The spring constant, K**,** of **1.4 [N/mm]** is used in design of the extension spring assembly. To achieve this characteristic of the spring, with the required size and dimensions to fit the clutch assembly, the Music Wire material was selected for the spring.

Physical Dimensions

The CAD model of the clutch assembly is used to determine the required size of the extension spring, needed to fit and function in the P-EM clutch assembly, based on the position of the spring during loaded and un-loaded process.

The following table, and Figure, (Table 7.3, and Figure 7.10), show the basic dimensions of the designed extension springs.

Physical Dimensions	[mm]	Spring Characteristics	-
OD	1.60 [mm]	K	1.4 [N/mm]
D_{wire}	0.28 [mm]	**Max. Initial Load**	0.4 [N]
R	0.8 [mm]	**Max. Spring Deflection**	3.5 [mm]
L_T	9.1 [mm]	**Max. Suggested Load**	5.1 [N]
L_{U-Wire}	7.5[mm]	**Material**	Music Wire
L_{Gap}	1.2 [mm]		

Table 7.3 **PN: 80020 Spring Specifications**

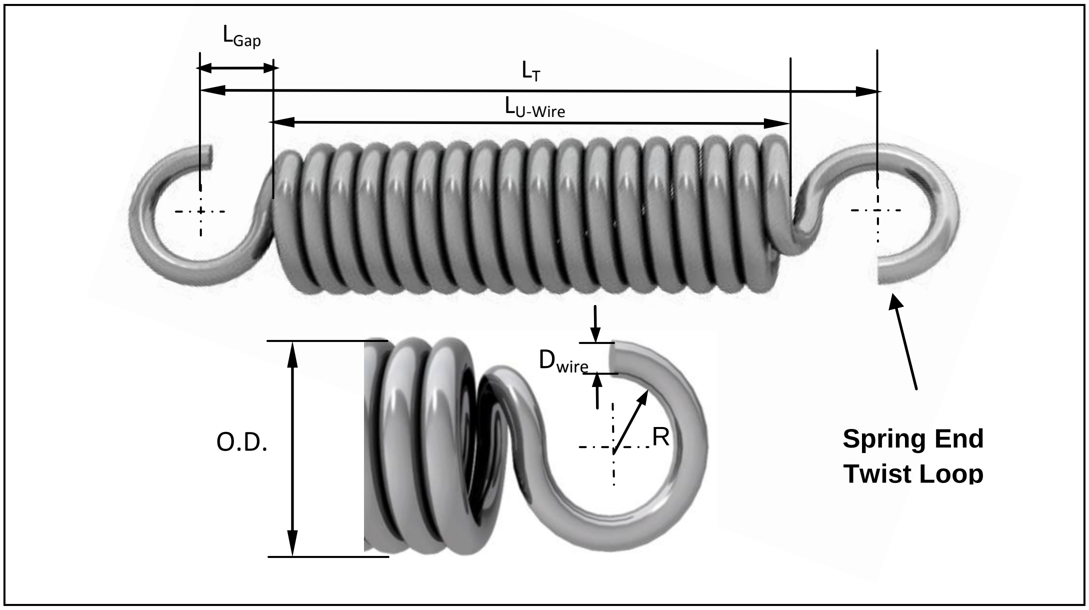


Fig.7.10 **Extension Spring Design**

7.5 Clutch Plate Design

7.5.1 Design of the Clutch Plate Teeth Geometry

The teeth of the top and the bottom clutch plates will engage under the clamping force created by the permanent magnet. In subsection 7.5.1.1, the teeth angle of the clutch plates will be calculated based on the maximum torque transfer capacity of the clutch assembly. In order to engage the clutch teeth properly, the both top and bottom clutch plates need to have teeth with same pressure angles, pitch, height, thickness, and radial dimensions. The detail of the design of the clutch teeth will be discussed in subsection 7.5.1.2.

7.5.1.1 Teeth Angle Calculations and Analysis

The figure 7.11 represents the free body diagram of the engaged teeth plates under applied torque of the clutch assembly. The derived formulas are used to calculate the required clamping force, generated by the magnetic field and induced by the permanent magnet, which in turn attracts the bottom and top plates. The $F_{clamping}$ is used to design and select the right permanent magnet. The required static torque for the clutch assembly is 30 Nm. The pitch radius of the engaged clutch plates is 0.0285 [m]. Pressure angle of 20 Degrees, (α), is used in the design of the serrated clutch plates.

$$F_T = \frac{\tau.\mathrm{n}}{\mathrm{r}_{\mathrm{pitch}}} = 1/2 \times \frac{30_{[\mathrm{Nm}]}.1.5}{0.0285_{[m]}} = \frac{1578.9}{2}[\mathrm{N}] \qquad \textbf{(Each plate)} \qquad \textbf{Eq.7.5.1}$$

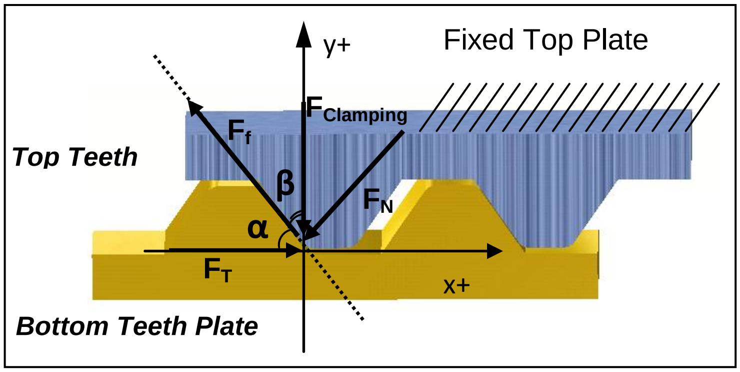


Fig.7.11 Free Body Diagram of the Teeth Clutch Plates

Assumptions

- Equations are derived under static conditions. No sudden or impulse loads are taken into consideration, since it is not in the scope of this thesis.
- A safety factor of (n=1.5) is used to ensure the success of the theoretical calculated values in selecting the right materials and correct design.
- The top plate is constrained relative to the bottom plate, and the reaction forces of the top and bottom plates are shown the FBD (Figure 7.11 and Table 7.4).

Coefficient of friction -Steel on Steel (Lubricated)	**μ= 0.35**
Normal Forces	**F_N=** [N]
Friction Forces	**F_f=** [N]
Force created by the torque (T=30 Nm)	**F_T=1052.63/2 [N]**
Clamping Force Created by the Magnet	**$F_{Clamping}$= 34.84 [N]**
Static Torque	**T=35 [N.m]**
Radius of the engaged teeth plates	**r=0.0285 [m]**
Pressure Angle of the Clutch teeth	**β=? [Degrees]**

Table 7.4 **Required Variables used in the equations**

Sum of forces along Y Axis, (Figure 6.4)

$$\sum F_y = 0 \Rightarrow -F_N \sin\beta + F_f \cos\beta - F_{clamping} = 0$$

$$As\ \ F_f = \mu F_N$$

$$\therefore -F_{clamping} = F_N(\tan\beta - \mu)$$ **Eq.7.5.2**

Sum of forces along X Axis, (Figure 6.4)

$$\sum F_x = 0 \Rightarrow F_T - F_N \cos\beta - F_f \sin\beta = 0$$

$$As\ \ F_f = \mu F_N$$

$$\therefore F_N = \frac{F_T}{(\mu\tan\beta + 1)}$$ **Eq.7.5.3**

Combing both Eq. 7.5.2 and 7.5.3 (Figure 6.4)

$$\mapsto T_{[Nm]} = \frac{\mu\tan\beta + 1}{(\tan\beta - \mu)} rF_{Clamping} = ZrF_{Clamping}$$ **Eq.7.5.4**

Equation 7.5.4, demonstrates that the torque carried by the serrated clutch depends on two constant values, the constant **coefficient of friction** of the teeth material (μ) and the **teeth angle** (β). The increase of Z will result in higher torque capacity of the clutch assembly. The value of Z will depend on both the angle of the teeth and the type of material selected for the clutch assembly, and thus Z can range from zero to infinity.

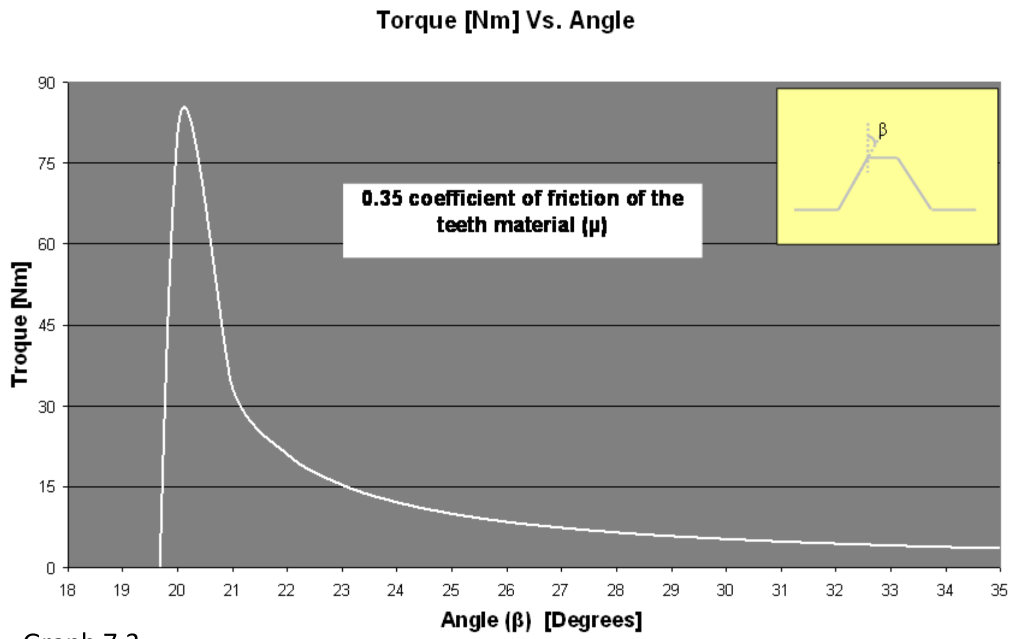
For instance if the value of Z become close to infinity for the designed clutch teeth, this can mean that the clutch mechanism can simply engage without a need of any clamping force, and this means the only limitations will be the strength of the clutch teeth, due to high stress concentration on the teeth, [4].This is an example of a square clutch teeth.

Sample Calculation

The equation 7.5.4 was used to graph the following figure, (Graph7.3). The value of the coefficient of friction was assumed to be 0.35. This value is assumed to be lowered due to possible oil migration on the surface, (coefficient of friction of oily steel surface is less than 0.4), [5].

The design specification of this clutch assembly is to withstand static torque of 35 [Nm]. A safety factor of 1.5 is used on the design of this clutch assembly; therefore, the seeking value of the clutch capacity is a 45 [Nm] static torque. Bad machining surface, migration of worn metallic dusts in between the teeth, and other similar factors are the reasons for using the safety factor of 1.5.

The white line on the following graph shows that the best selection for the teeth angle range is located in between 20 to 21 degrees, and therefore, based on the known engineering metrics (external noise and etc.), and the calculations, it is safe to use the **20 degree angle** for the design of the clutch teeth. Nevertheless, it is also important to note that these values are all theoretical, and the real results will heavily rely on the quality of the machined clutch plates.



Graph 7.3

7.5.1.2 Clutch Teeth Geometry

The geometry of the clutch teeth is designed as such to make it possible to be machined for fabrication of the prototype model of the P-EM clutch assembly. Since the purpose of this study is to identify the functionality of the design, and yet, no manufacturing planes are in line with the study of this design, the clutch plates will be designed for conventional machining methods, such as turning and milling.

The serrated clutch plates play crucial roles in the functionality of this clutch assembly. In order to reach the specified torque capacity of 45 [N.m], it is important to design and fabricate the plates with tight geometry and dimensional tolerances.

High tolerances will assure better surface contact in between the engaged clutch teeth, and therefore, increase the chances of carrying the maximum torque capacity that this clutch is designed for. The theoretical calculations are conducted based on the assumption of perfect surface contact in between the assembly components, although in reality, these tolerances are not completely achievable, thus could lead to failure of the part.

The higher percentage of the teeth in contact with each other during the engagement, means lower the stress load distribution in between the teeth. Therefore, it is possible to carry the torque capacity without shearing the clutch teeth. For instance, out of spec clutch plates might reduce engagement teeth contact, and this clearly means that in this case lower number of teeth will carry all of the loadings of the clutch assembly, and this can lead to clutch teeth failure. Nonetheless, the purpose of this thesis study is to validate the concept of EM-P clutch mechanism, and further study is required to design and optimize the clutch components for manufacturability.

7.5.2 Geometry of the Clutch Plate

The design of the clutch assembly requires the clutch plates to be pulled by extension springs. These springs are designed to separate the clutch plates away from the permanent magnet, which in other words, the springs are used to move each top clutch plates away from the **effective magnetic field** of the permanent magnet. As it was discussed in section 7.2.1, to disengage the clutch assembly, the magnetic flux density of the permanent magnet will be reduced by the electromagnetic field, therefore, the springs will be able to overcome the clamping force of the permanent magnet, and move the plates away from the effective magnetic field area. This simply means that once the permanent magnet has regained its full Magnetic Remanence, it will not be able to attract the plates back into the engaged position. Air gap acts as a resistance to magnetic field, and sudden reduction in the magnetic flux density is expected as the plates move away from the magnet, therefore, small forces are exerted upon the clutch plates, in the disengaged position.

The design of the springs will requires knowledge of the theoretical distance required for the clutch plates to move away from the effective magnetic flux zone. In section 7.2.1, the theoretical effective zone of the magnetic flux (Y), was calculated to be more than 3.5 mm away from the surface of the ring permanent magnet. This means that locating the clutch plates 3.5 mm away from the surface of the magnet will not allow the magnet to attract the plates back into the engaged position. This information is very critical in the design of the key-seat that helps the clutch plates to slide back and forth, guided by the slider plate, (Figure 7.12 ,7.13, and 9.6)

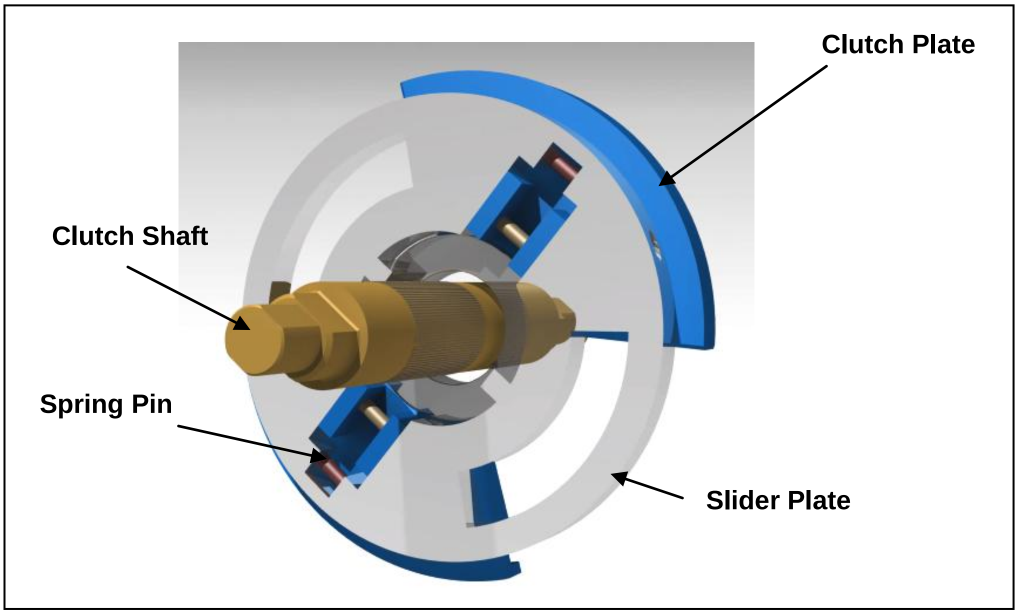


Fig.7.12 **Bottom View of the Two Clutch Plates and the Slider Plate**

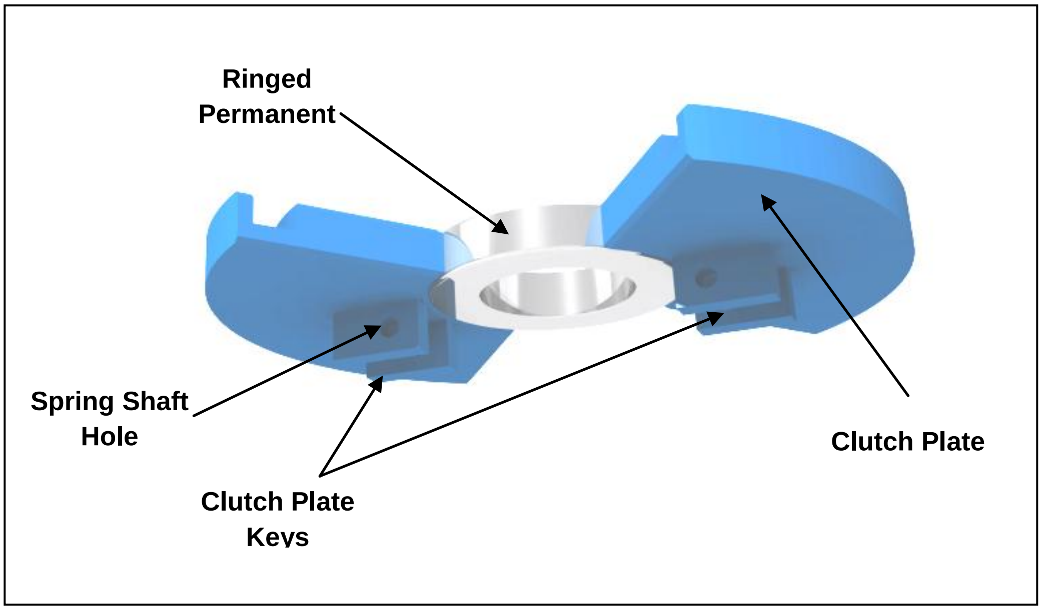


Fig.7.13 **Bottom View of the Two Clutch Plates and the Permanent Magnet**

8.0 Design for Fabrication and Assembly

The first prototype of the P-EM Clutch assembly will be machined using series of turning, and milling. The prototype is used to validate the theoretical calculations, and optimize the design by testing the product. Nevertheless, the fabrication and assembly process requires certain dimensional and geometrical tolerances, (GD&T), for each of the components of the assembly, and this will help to ensure the correct functionality of the assembly, and it is the key for the successful engineering validation testing, (EVT).

This section will point out some of the assembly components that have important effects on the functionality of the P-EM clutch assembly.

8.1 Permanent Magnet Ring and Stator Housing

The permanent magnet will be assembled on top of the stator housing, using **Interference Fit method**. This means that the tolerance of the permanent magnet ring hole, and the stator housing cylinder will be selected in such was that the ring magnet will have slight interference with the stator housing,(figure 8.1)

The most important key in the assembly of this component is the type of material used for the permanent magnet and the stator housing.

The permanent magnet is made from a material called Neodymium **(See Sections 5.3 and 7.1)**, which is a brittle material. The stator housing is designed from a normalized

SAE 1015 (Low Carbon Steel alloy Tensile Strength of 61500 lb/in^2), and therefore, has higher ductility compared to Neodymium.

To assemble the ring magnet on top of the stator housing, a method of engagement is required, however, slight interference fit using shrink fitting of the permanent magnet over the cooled stator housing will be the best option.

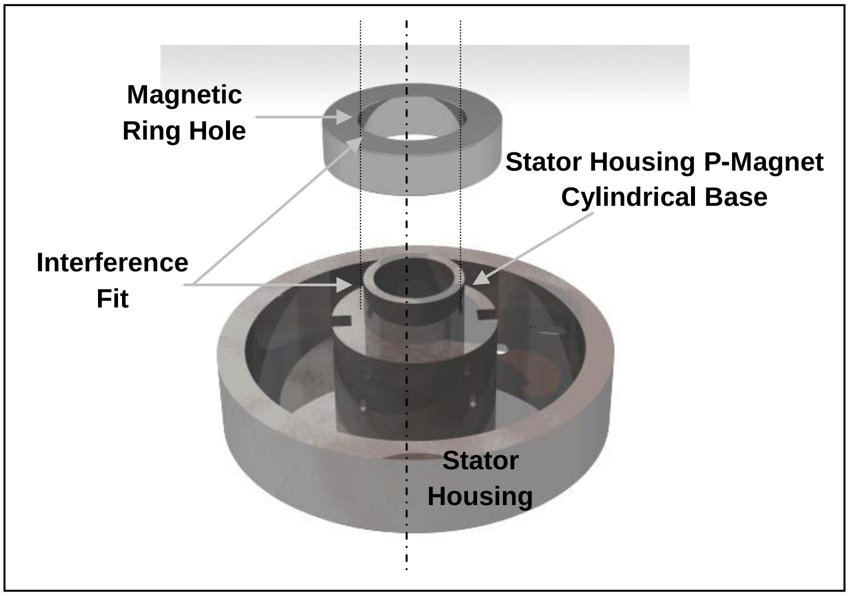


Fig.8.1 **Stator Housing and Magnet Ring Interference Fit Line**

8.1.1 GD&T

Metric Basic Hole System

Using metric tolerance specifications for **Hole Basic System**, H7/p6 preferred metric tolerance-fits are selected for the design of the permanent magnet and the stator housing. The H7/s6 is a **locational interference fit**, meaning the two parts can fit with adequate alignment, rigidity and positional accuracy without any need to high force press-fit process. Due to brittleness of Neyo35, press-fit process was avoided to prevent any damages to the permanent magnet ring, [5].

The basic size of the permanent magnet ring hole is 15.00 [mm], and H7 represents a **tolerance of -0/+0.018 [mm].** Meaning at Maximum Material Conditions, (MMC), and the internal diameter of the permanent magnet ring will be 15.018 [mm].

The shaft tolerances of p6, +0.018/+0.029 [mm], were selected based on the nominal outside diameter, 15.0[mm]. At MMC the OD. of the base cylinder will be 15.029 [mm] and therefore, there will exist an interference fit of - 0.029 [mm].

8. 1.1.1 Shrink Fit

To shrink fit the permanent magnet over the stator housing base, the temperature of the stator assembly will be reduced using dry-ice, (Carbon Dioxide). Dry-ice will be able to drop the temperature of the stator housing close to -60^{oC}, and as an estimate, this can result into 0.05 mm radial reduction on a steel bar with 25 mm diameter, [5].

As it was mentioned in Section 8.1.1, the maximum possible interference of - 0.029 [mm] will exist in the tolerance design of the magnet and the base shaft, and cooling the stator housing using dry-ice will reduce the interference of two parts, therefore, the two pieces can be assembled without damaging the brittle Neodymium permanent magnet.

Shrink fitting will prevent any damages that could result during the press fitting process, however, this type of design is only used for the prototype model. For mass production purposes, this method can be costly, and other simpler interference methods can be used in the design of the final manufactured part.

8.1.2 Geometrical Tolerances

As it was indicated before, the capacity of the torque transfer of the clutch assembly relies on the clamping force generated by the permanent magnet ring. The quality and the clamping force generated in between the bottom clutch plates and the permanent magnet will heavily rely on the outside diametrical surface of both permanent magnet and the clutch plate.

In case of any uneven surface or dimensional changes in the curved engaging surfaces, gaps will appear in between the mating surface of the permanent magnet and the clutch plates. Magnetic flux leakage will appear as a result of any mating surface gaps. Flux leakage will cause sudden reduction in clamping force, and therefore, the clutch torque capacity will be reduced**,(Figure 7.12).**

Therefore, it is clear that tight tolerances are needed to keep the outside diametrical surface of the permanent magnet ring and the clutch plates within acceptable range. The safety factor of 1.5 is used in case of possibility of gaps and any other negative factors that can affect the functionality of the assembly, however, good GD&T will help the design to reduce the gaps in most effective way.

The outside diameter of the ring magnet has a diameter of 25.00 [mm], and dimensional tolerance of 0/+0.01 is used to keep the MMC closed to the internal diameter of the clutch plate assembly.

The Run Out feature with value of 0.008[mm] with respect to the internal diameter of the ring circle, (Datum A), is used to make sure that the circularity of the ring magnet is within acceptable tolerance zone. The run out feature is simply checked by turning the ring magnet around its axis centre, and monitoring the change in circularity using a dial indicator, at a fixed location.

9.0 Prototype

The original plan for the fabrication of the prototype was using EDM (Electric Discharge Machining) method to machine the top, and bottom plates. However, the high cost of the EDM was out of the allowable budget of this project, therefore, conventional turning and milling operations were the best choices available for the fabrication of the prototype. The EM-P Clutch prototype is needed to validate the functionality of the clutch design, however, using conventional machining methods selected for this thesis project come with the risk of out of specification tolerances needed to determine the functionality of this clutch mechanism. The complex geometry of this mechanism requires professional and high precision machines and the budget of this project simply would not allow such selection. Thus, conventional turning and milling were used to machine the components. The following sections will describe certain methods and approaches used to fabricate the prototype.

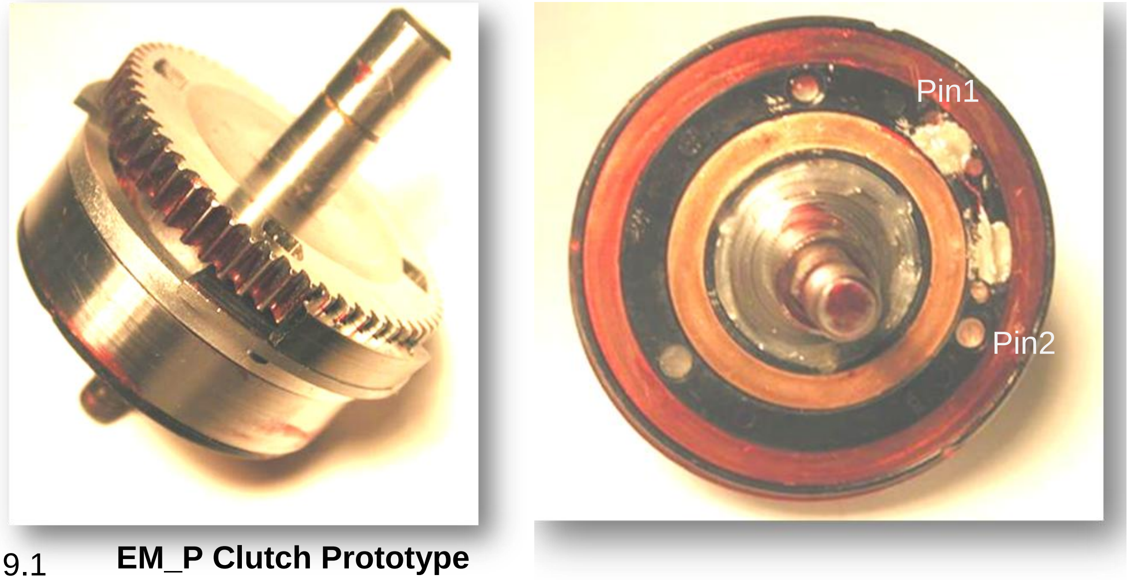

Side View **Bottom View**

Fig.9.1 **EM_P Clutch Prototype**

9.1 Fabrication of Top and Bottom Clutch Plates

The top-plate clutch component is one of the components that carries the torque output of the motor and transfers the power through the rest of the clutch components. The top -plate is assembled with the GM-T900 Wheel Worm Gear using existing four keys, (figure 9.3). Four key seats are machined and the Worm Wheel is placed on top of the top clutch plate in order to carry torque during engagement period. The top-plate contains the external clutch teeth that are used to engage with the two bottom-plates. Therefore, it is important to select a material with higher tensile and shear stress in order to be able to handle the required stress applied during torque transfer. Nonetheless, the top-plate needs to be designed and fabricated using a material with low magnetic permeability, such as Bronze, Brass, Copper, Aluminum, or Stainless Steel. Stainless Steel (AISI 301 with 600 MPa tensile strength) was the best material, and it contains non-magnetic characteristic due to its Austenitic proper, [8].

Fabrication Problem 1:

Conventional machining approach has limited capabilities and generating the desired gear teeth profile for the serrated clutch plates is almost an impossible approach. As mentioned before, other methods, (EDM WIRE CUT and Hubs) are costly.

Solution:

To solve this issue, a set of spur gear and internal ring gears were purchased through KHK Gear Manufacturer. The Gear used for the top-plate component was an Stainless Steel Spur gear with 60 teeth, Gear Module of 1, and outside diameter of 60mm. And the Internal Ring gear was a 1040 Mild Steel with Gear Module of 1, 60 gear teeth ,diameter of 60 mm and pressure angle of 20 degrees. Even thought the selected gears did not function and contain the same dimensions that were designed for the prototype model, they were believed to be able to function similar to the designed plate teeth.

Fig.9.2 **Machined Top Clutch Plate**

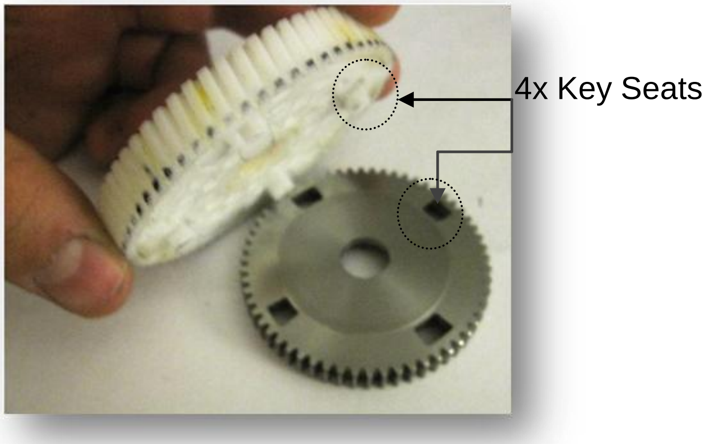


Fig.9.3 **GMT-900 Worm Gear & Top Clutch Plate**

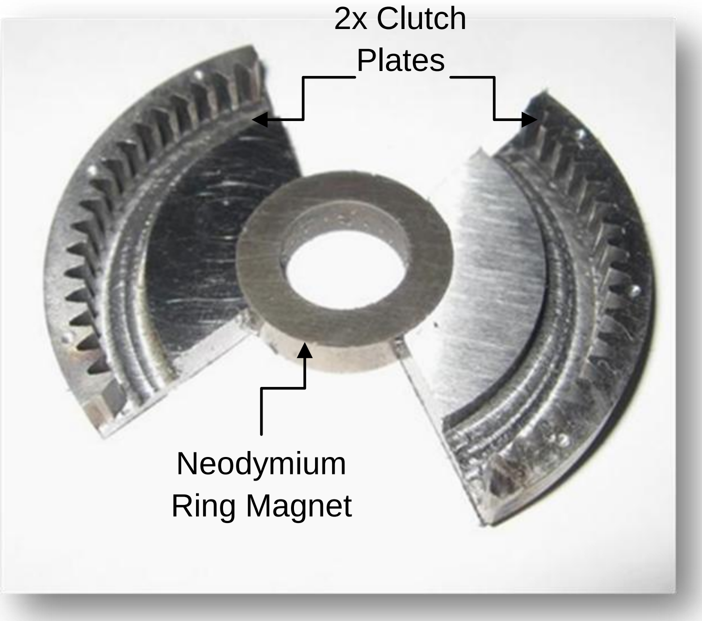


Fig.9.4 **Machined Bottom Clutch Plate & Ring Magnet**

9.2 Fabrication of Slider Plate

Machining the slider-plate was one of the challenging tasks and it took over 7 hours of machining to fabricate the part, however, in order to mount the slide-keys,(figure 9.5), a dummy shaft or so called assembly fixture was machined to replicate the geometry of the clutch stator subassembly with more accessibility, (figure 9.6).

This fixture was used to glue the slider-keys to the bottom surface of the bottom-plates and using a number zero set screw, mount the slider keys to the bottom-plates. This required precision drilling and tapping.

Nonetheless, the fixture could not offer high accuracy that was needed on the positional tolerance of the two slider keys, (+/- 0.009”), and this is one of sources of errors present in the fabrication process.

In future, it is important to machine this part using EDM wire cut method and achieve the accuracy needed. Out of spec positional tolerances can cause friction and even interference between the bottom-plates and the slier-plate. Meaning the bottom plates cannot freely slide back and forth into engaged/disengaged configurations.

Fig.9.5 **Bottom Plate**

Alignment Fixture

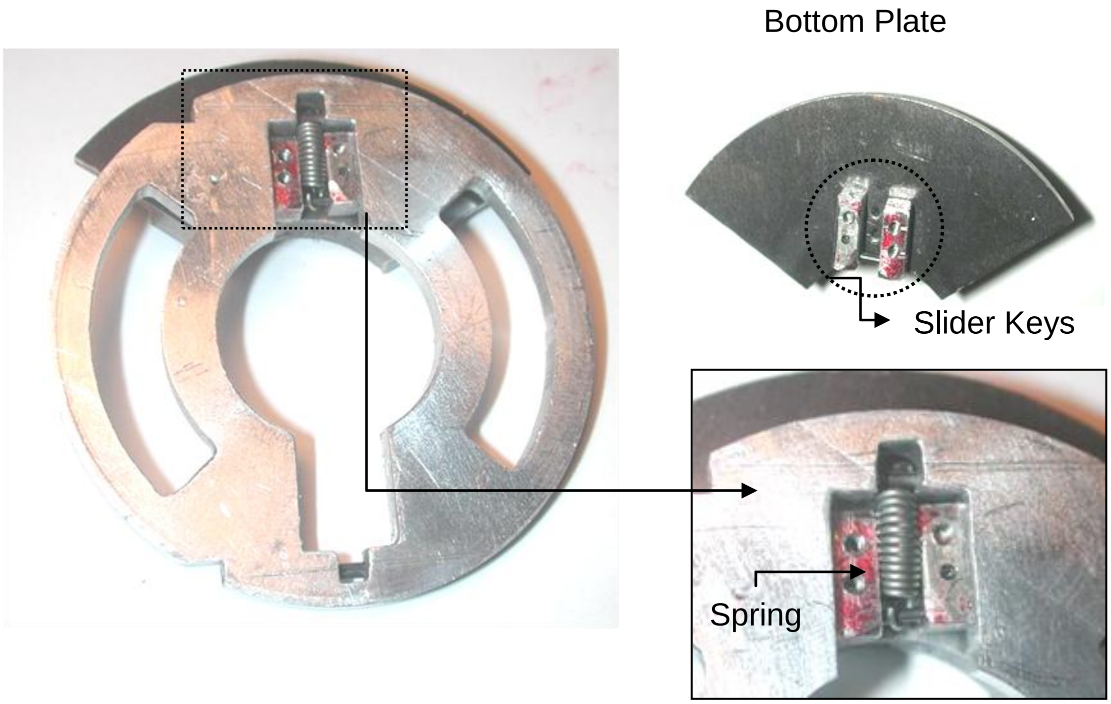


Fig.9.6 **Slider Plate and the Bottom Plate**

Figure 9.6 shows the spring coil assembled in between the two spring pins located on slider-plate and the bottom-plate. The slider-key located in the centre of the bottom -plate will help the bottom-plate to slide away from engaged configuration into disengaged configuration, under the tension of the loaded spring. It is important to have smooth and non frictional slider for both plates and this is defined by the positional tolerances for both slider keys. The clutch malfunctions are expected if the slide-keys are not positioned according to the engineering drawings.

One of the downsides of conventional machining and limited time and budget was such unavoidable tolerance losses that had compromised the functionality of the prototype.

10.0 Design of Experiments (DOE)

In order to prove the theoretical calculations used in the design process of the EM-P clutch mechanism, the following DOE was conducted to observe the effects of electromagnetic field generated by the stator coiling on the permanent magnet.

Test Setup

The projected magnetic field of two common magnetic poles (N to N) can weaken the overall magnetic field. For instance, placing two permanent magnets with common magnetic poles near each other will create a repelling force and therefore the magnetic flux density will be reduced. The opposite of this claim is also true, and uncommon poles of two permanent magnets placed near each other will increase the magnetic flux density, (Section 7.3.2).

In this experiment, a one axis Gauss measurement sensor is used to measure the magnetic field density (B) of the permanent magnet placed on top the stator sub-assembly,(figure 10.1). The calculations used to design the stator housing, the coil sub-assembly, the location of the slider plate, and the permanent magnet selection rely on one important engineering metric, and that is the effect of the electromagnetic field exposed onto the magnetic field of the permanent magnet. The functionality of the clutch assembly heavily depends on the concept of weakening and strengthening magnetic field of the permanent magnet using electromagnetism.

The 22151Y Gauss meter is a digital magnetic field sensor that converts the measured magnetic field into analog voltage values. Using an Analog to Digital conversion circuit, the filtered analog signals are transferred into digital or Binary signals. Using a PIC Microcontroller (or computer), the digital signals are converted into actual measurement in unit of Tesla or Gauss.

The magnetic field density of the permanent magnet is measured as follow: (figure 10.1)

1- Measure the North Pole of the magnetic flux density of the magnetic ring in 0 [mm] away from the outer surface of the ring. Sensor touching the surface of the magnet, and this means limited air gaps, (figure 10.1).
2- The similar measurement are taken at distanced of 2 [mm] and 4 [mm] away from the outer surface of the magnetic ring, (figure 10.1).

3- Steps 1-2 are repeated as the electromagnetic coil of the stator sub-assembly is energized using +12 [V] on pin 1 and Ground on pin2,(figure 9.1) .

4- Steps 1-3 are repeated as the electromagnetic coil of the stator sub-assembly is energized using Ground on pin 1 and +12 [V] on pin2, (figure 9.1).

It is important to note that the location of the permanent magnet assembled into the clutch mechanism is calibrated according to the magnetic field generated by the electromagnetic coil. (See section 7.1)

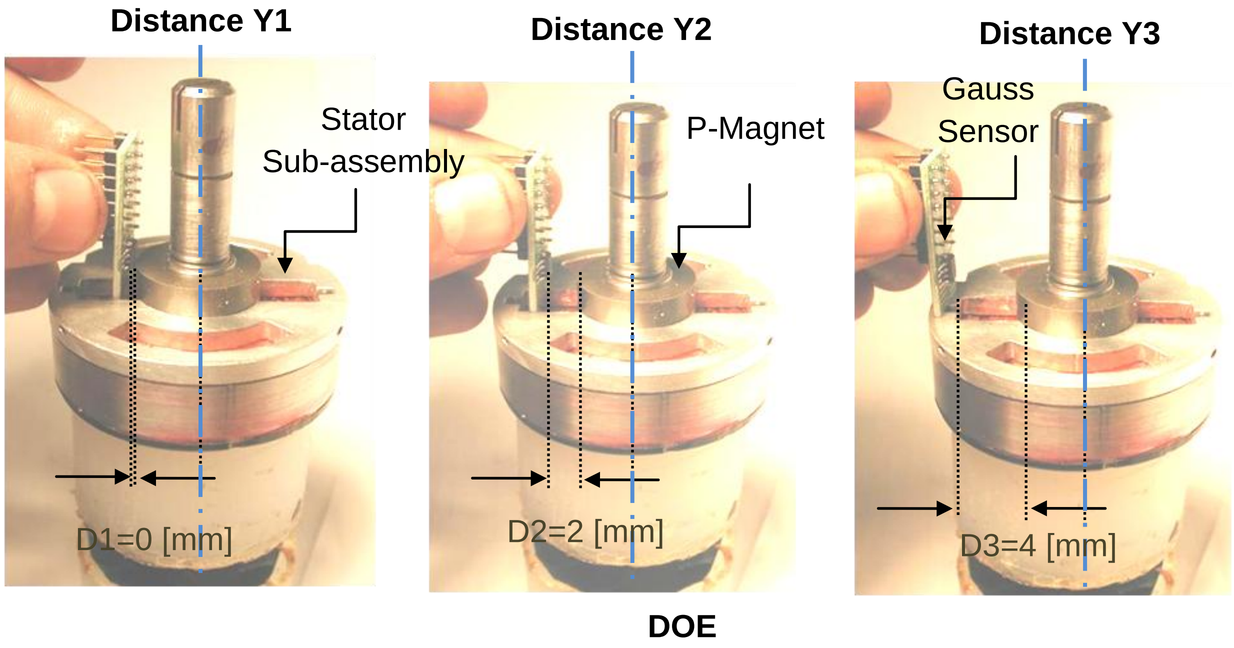


Fig.10.1 **Magnetic Field Density Measurement on Clutch Stator Sub-Assembly**

10.1 Results

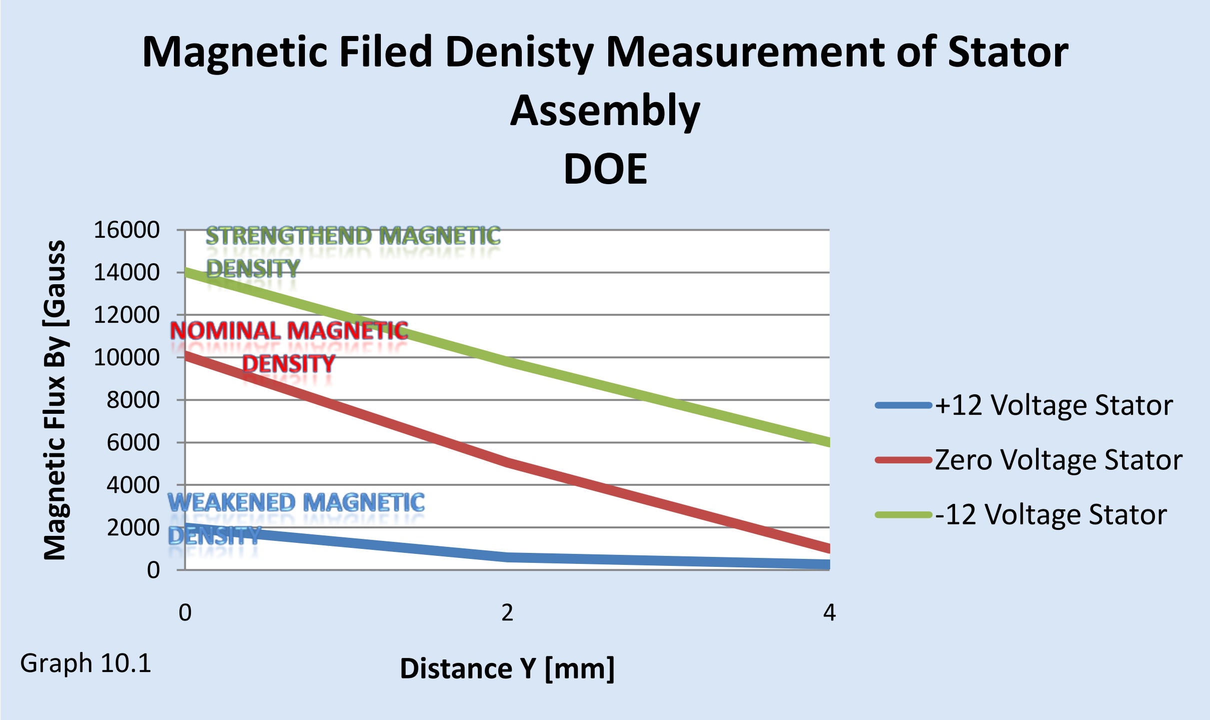
The data gathered from the DOE can be compared to theoretical calculation on sections 7.2, 7.3.2.1, and 7.3.2.2. Graph 7.2 represents the theoretical nominal magnetic flux density as the bottom-plates move away from the outer surface of the (O.D. 25[mm]) magnetic ring.

The calculations on sections 7.3.2.1 and 7.3.2.2 represent the effect of the electromagnetic field of the stator on the permanent magnet ring, while the permanent magnet was weakened or strengthen.

Nevertheless, the physical measurements of the experiment can be used to compare results for all three configurations, (Nominal, Strengthened and Weakened P-Magnet Field).

Sensor to Magnet Distance (Y) [mm]	Stator Voltage [v]	Magnetic Field Density (B) [Gauss]
0	0 [v]	10092.1
2	0	5050.2
4	0	1002.7
0	12	2000.3
2	12	603.5
4	12	264.2
0	−12	14012.6
2	−12	9801.1
4	−12	6014.1

Table.10.1 **Sensor Measurement Results**



Graph 10.1

11.0 Discussion

11.1 Design of Experiments

The data collected from the DOE demonstrates the effects of the electromagnetic field on the permanent magnet's magnetic field density, (Graph 10.1).

The nominal measurements of the permanent magnet over distance displacement of 4[mm], (Red Line on Graph 10.1), are compared to the theoretical calculated magnetic field density of the permanent magnet over the distance displacement of 4 [mm]. Comparing both results (Graph 7.2 and 10.1), we can conclude that there is 10.3% of error for the calculated values. The theoretical values are 10.5 % smaller than the actual measurement values.

11.1.1 Sources of Error:

Dimensional error such as out of spec permanent magnet ring can affect the measurement.

The strength of the permanent magnet can be higher than the desired value that was specified in the engineering document of the magnet.

The estimate distance between the permanent magnet and the sensor can cause such errors. Potentially, accurate measurement fixtures can be used to gather more accurate results.

High Frequency noises captured by the sensors can cause such errors. In this case, a 200 Khz low-pass filter was used to cut off unwanted noise, however, it is possible that some of the good results were also cut off by the filter.

Round off errors which were generated by the microcontroller could be another source of error.

The 10.3% error on the actual values of the experiments and theoretical calculated values could have been due to improper usage of formulas. Simplified formulas used in the design of the EM-P clutch mechanism are only estimates and this experiments proves that there is about 10.3% errors in the calculated values. It is also possible that there are certain level of measurement errors involved in the DOE procedure, however, error in calculations could generate fault design.

The following subsection will discuss whether the designed clutch mechanism was able to function according to the design plan.

11.2 Prototype Model

The prototype model of the clutch mechanism does not function according to the specifications. The designed springs are not strong enough to overcome the forces created by the permanent magnet when the magnetic flux density has reduced. The reason for the lack of functionality is the error in calculations. As mentioned in the previous section, the theoretical calculations and the actual measurements were off by 10.5 %, and since the design of this clutch mechanism does not allow for any major variation in the force result balance, it is clear that the clutch mechanism will not function.

One of the other important factors was the out of spec prototype parts, which were accepted due to limited time spam of this project. The stator housing inside diameter was machined out of spec, by -5 mm under sized. During the prototyping period it was believed that it will not have any major affects on the functionality of the part, however, the smaller coil wire housing means that lower number of coil wire turns can be placed inside of the stator housing and therefore smaller electromagnetic field will be generated. This can affect the functionality and prevent the clutch mechanism from disengaging.

The locational tolerances used in the fabrication of the slider-keys used in the bottom plates are one of the possible problems to the malfunctioning prototype. The slider-plate is used to guide both bottom-plates into engaged/disengaged configurations, nevertheless, this slide action requires smooth and less frictional movements. Out of spec slider-keys (positional tolerances) are believed to be causing interference. The initial assessment indicated that the designed spring (PN: 80020 Section 7.4) is not capable of creating the needed tensional force to disengaged the bottom clutch plates as the permanent magnet has weakened. Several different springs with different characteristics were used to solve this problem. Springs such as B3-3 (K=3.5N/mm, L=6.4mm), 80061 (K=2.5 N/mm, L=69.7mm),and ZZ4-49 (K=2.6 N/mm, L=10.1mm) were used to solve this problem. However, it appeared that the interference caused by the slider-keys have been creating the issue with the clutch slider plate and therefore preventing the clutch assembly from disengagement. The solution to this problem required two re-machined bottom plates and this was simply not possible due to limited time and budget. However, in near further this project will focus on redesigning the bottom-plates and machining new parts with machining processes that are capable of achieving the required positional tolerances, (i.e. Wire EDM)

One of the other solutions to the malfunctioning clutch mechanism was using thinner gage stator coil wires, (26 AWG instead of 24 AWG), to achieve higher number of coil turns in the limited space of the stator assembly. This method did not help and the clutch was not able to disengage, (figure11.1).

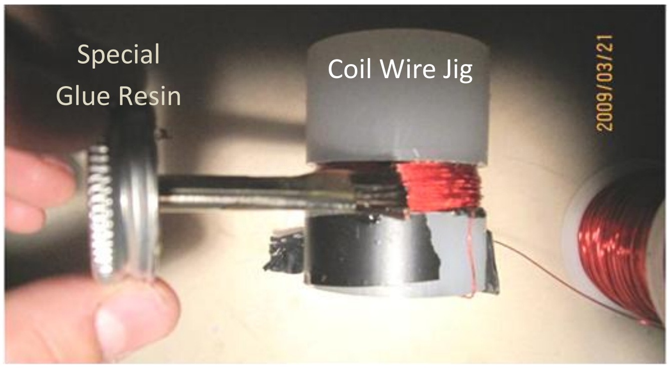


Fig.11.1 **26 AWG Wire Wrapping Jig**

12.0 Conclusion

The DOE experiment conducted on the prototype housing stator indicated that the actual values do not match with the theoretical calculations. Nevertheless, the final prototype model did not function and this can mean that future design modifications and calculations are needed to identify the proper design of this clutch.

One of mistakes made during this project was the lack of software simulations. Software simulations use iterative and numerical approaches to show the effect of the electromagnetic field on the permanent magnet (i.e. Comsol). This means that this project can be taken over by other students as future thesis study. The mechanism will function, and it is matter of right calculations, better design, higher budget, and more man power.

The new designs such as the design of this clutch mechanism usually need to be revised again and again, until the errors and mistakes of the engineers have been eliminated. The first iteration of the EM-P clutch assembly was not a success, however, the results and experiments conducted to design the first version of this mechanism are nothing but initial steps and useful tools to path of a complete and functioning product.

Engineering design is about testing, experimenting and changing engineering metrics that affect the design. In the design process of the EM-P clutch mechanism there were several important engineering metrics. Some of these metrics were nothing but simple tolerances, however, some of the metrics related to actual theoretical calculations and assumptions which the design was based upon. Nonetheless, it is important to identify the sources of errors and the noises in the system, and using more tools and more known approaches to get closer to the working model and working design of the clutch mechanism. The final word is the assurance of the theoretical and engineering concept behind the design, and the failure to fabricate a working product was nothing but errors, mistakes and out of spec components that lead to this failure. Future work on this clutch mechanism is important, and in near future, this project will be my graduate thesis and the mistakes made will be corrected and once again lessons will be learned.

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Appendix A

Terminologies

Acronym	Terminology	Definition
PLG	Power Liftgate	A mechanical device designed for closure of the vehicle gate
EM	Electromagnetic Field	Magnetic field generated by current running through a conductive wire.
EM-P	Electromagnetic-Permanent Magnet	A new clutch mechanism that use both Electromagnets and Permanent Magnets to function.
-	Teeth Clutch	A torque transferring mechanism that uses serrated plates to engage and transfer torque from the motor to the gear box.
-	Life Cycle	Life Cycle=10'000 Cycles
GM-T 900		GM-T900 is referred to General Motor's Vehicle platform *(SUV Tahoe)*
-	Third Position Hold PLG	Next generation of PLGs that allow the driver to select the gate travel angles, (ex. Short garage ceiling, Canoe on top of the car and …)
$F_{CLamping}$	Clamping Force	Clamping force is referred to the force created by the magnetic field on the clutch plates to engage the clutch for torque transferring purpose. It is perpendicular to the surface of the piece, and it could be referred to the normal force as well,**[N].** *Section 7.2*
-	Effective Distance or Effective Magnetic Zone	Effective magnetic zone is referred to the distance or the zone that the magnetic field has smaller attraction on the piece. *Section 7.2.1*
-	Stator subassembly	The stator subassembly is consisted of the magnetic coil wires, the cylindrical core or housing that contains the coiling. This component is used to generate the electromagnetic field of the clutch mechanism. *Section 7.3,*
-	Solenoid Coil or EM Coil	It is referred to the helically wrapped coated copper wire that is used in the stator subassembly to generate the EM field. *Section 7.3.1*
H	Magnetic Field Intensity	A current running through a piece of wire can create a magnetic field circling around the wire, and this magnetic field is called the Magnetic Field Intensity, **[Webbers or A/m]** *Section 5.3*
B or Φ	Magnetic Flux Density	Measure of the level of magnetic field (strength) in a magnetic field**,[Tesla or Gauss**] *Section 5.3*
H_c	*Magnetic Coercivity*	,which is defined by the amount of Magnetic Field intensity required to reduce the magnetic flux density of the permanent magnets to zero., **[Webbers or A/m]** *Section 5.3*
μ	Magnetic Permeability	Material property which defines the effects of the material exposed in a magnetic field. It could also be known as the magnetic resistivity or conductivity of material. (Air has low magnetic permeability and iron has high magnetic permeability). [N/A^2] *Section 5.3*
μ_o	Permeability of Air	$\mu_o=4\pi x10^{-7}$ [N/A^2] *Section 5.3*
χ	Susceptibility	It is referred to the amount of energy required to magnetize the material. *Section 5.3*
H-B	H-B Curve	Referred to the Magnetic Intensity verses Magnetic Flux density hysteresis curve *Section 5.3*
B_r	Magnetic Remanence	Magnetic Remanence is the level of magnetic flux density left inside of the material during the magnetization procedure. *Section 5.3*
N35	Neodymium 35	Rare earth Element used to fabricate high strength Magnets. *Section 7.1*
MMC	Maximum Material Condition	This term is used with Geometrical Tolerances, and refers to the condition of the tolerances when the part is the heaviest, or contains more material.