ABSTRACT

This report examines the design and analysis of a Two-pole Electro-Permanent magnetic clamp (EPMC) - a modern workpiece clamping solution. An iterative design approach has been adopted to arrive at a reasonable dimension of the overall device which will satisfy the clamping force requirement. Initial analysis was done using MCA in Simulink, then primary optimization was performed using LUA script interfaced with FEMM package. The final dimensions were tuned using ANSYS Optimetrics and ANSYS Maxwell.

I. INTRODUCTION

Almost every traditional material removal process requires that the workpiece be held securely in the fixture or support. Since it requires a large constant clamping force which shall resist the forces generated in the material removal process, there may be chances of loosening-up of the clamp, or heating-up of the workpiece, or its position misalignment. Therefore, an EPMC provides a very efficient solution to this problem. It provides a magnetic clamping force to hold the workpiece made of ferromagnetic materials during machining. The EPMC which we are modelling consists of a Ferromagnetic pole and casing made of Steel-1025, two different Permanent Magnets (PMs); one having high coercivity (NdFeB), & another having low coercivity (AlNiCo). The low coercivity magnet is wrapped around with several turns of current-carrying copper wire. The copper wire is wound in a direction such that it produces a magnetic field in a direction opposite to the inherent magnetic field of low coercivity magnet. The EPMC device is in OFF condition (figure 1) while the workpiece is adjusted and fixed on the platform. After setting the workpiece, a short-timed large current pulse is passed which reverses the polarity of the AlNiCo magnets. This is referred as the ON condition (figure 2) where the magnetic flux passes through the workpiece providing it a maximum downward magnetic clamping force. The prime aspect that governs the working of EPMC is the magnetization direction of the PMs used in the device in OFF and ON condition. Magnetic flux always passes through a least reluctance path.

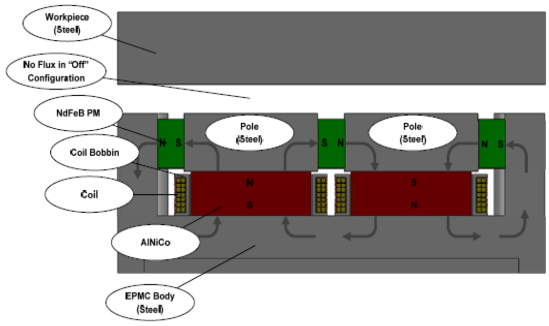

Figure 1 – EPMC device in OFF Configuration

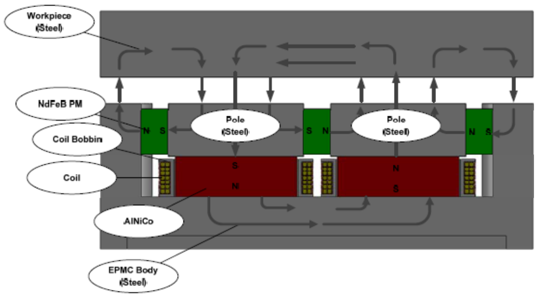

Figure 2- EPMC device in ON configuration

In OFF condition, the least reluctance path is through the EPMC body whereas in ON condition the least reluctance path is through the workpiece. In ON condition, the reluctance force helps in clamping the workpiece.

I.A. Performance Objectives

The primary objective of the project is to model and analyse the EPMC device by applying a combination of concepts learnt throughout the course to achieve the following set of goals:

- Achieve a vertical reluctance force as high as 1500 lbs in the '*on' configuration* by maximizing magnetic flux density at the interface of magnetized surface and workpiece.
- Ensure that flux is restricted inside the EPMC body in OFF configuration.
- Evaluate trade-offs in cost/volume by changing material grades of the magnets.
- To minimize the overall weight and size of the device.

I.B. Design variables & parameters

There are a few design parameters including materials and dimensions which are fixed are as follows:

1. The material for EPMC casing and Pole-piece is grade 1025-Steel.
2. The length and depth of each Pole-piece is 50 mm.
3. The centres of the two poles are 60 mm apart. There is an NdFeB magnet placed centrally between two Pole-pieces. This constraint also fixes the length of NdFeB equal to 10 mm.
4. The length and depth of AlNiCo magnet is constrained by coil bobbin whose internal dimensions are 46 mm x 46 mm. The height of AlNiCo is limited to 14 mm.
5. A minute airgap of 0.1 mm is assumed to between workpiece and EPMC upper surface. At all other material interfaces, perfect contact is assumed.

To achieve optimum design, several methods have been implemented in conjunction with each other. Some intuitive choices have also been made for the material based on their Magnetic coercivity. They are discussed in the subsequent section.

II. METHODOLOGIES

To describe the problem at hand, we have defined following design variables;

L_{nx} - Length of NdFeB magnets, mm

L_{ny} - Height of NdFeB magnets, mm

L_{px} - Length of Pole-piece, mm

L_{py} - Height of Pole-piece, mm

L_{ax} - Length of AlNiCo magnets, mm

L_{ay} - Height of AlNiCo magnets, mm

L_c - EPMC casing thickness, mm

L_z - Depth into the page, mm

L_{top} - NdFeB Position from top surface, mm

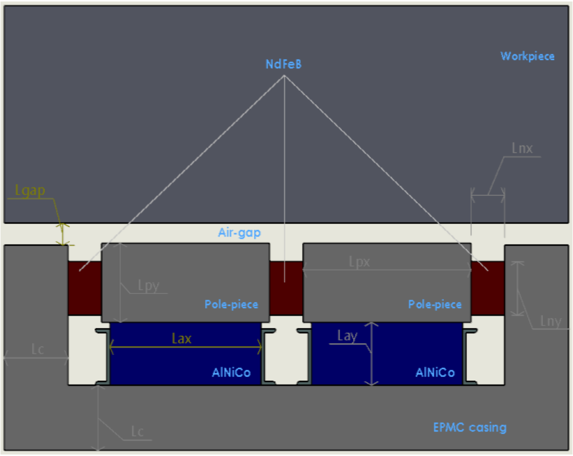

Figure 3- Cross-sectional layout of the clamp

After defining design variables, the next stage is to analyse the system with different design parameters starting with a 1-D analytical method – 'Magnetic Circuit Analysis'. This method gives us a good starting point for design variables. Being a 1-D analysis method, MCA has some limitations. Therefore, we implemented 2-D planar analysis which is essentially a Finite Element method in magnetostatics. FEMM allows us to modify the design parameters iteratively using Lua script. Following it, we also perform a 3-D analysis of our model using ANSYS Maxwell 3D software.

At last, we have made a comparison between each analysis method and based our design recommendation according to 3-D analysis which is closer to practical scenario.

The design procedure starts with considering the OFF configuration of EPMC. We want to achieve a least amount of downward tending force in OFF condition. When OFF condition parameters are optimized, we proceed to ON configuration.

II.A. Magnetic Circuit Analysis (MCA)

MCA is an analytical method that uses electrical circuit analogy to solve magnetic circuits. Flux, MMF and Reluctance in magnetic circuits are analogous to current, voltage and resistance in electric circuits. For our system, only ON condition Magnetic circuit is considered.

To perform magnetic circuit analysis, the permanent magnets were considered as an equivalent flux source and a reluctance. The reluctance of steel pole, steel case and the workpiece were neglected for simplifying the analysis. Only reluctances due to air gaps between workpiece and the steel pole were considered. In MCA, all design variables are involved except L_{py} and L_{top}.

Table 1 – Reluctances in Magnetic Circuit

Var.	Equation	Definition
Ra	$L_{ay} / (\mu_0 \mu_r A_a)$	Reluctance of AlNiCo magnet
Rg	$L_g / (\mu_0 A_g)$	Reluctance of Air-gap
Rn	$L_{nx} / (\mu_0 \mu_r A_n)$	Reluctance of NdFeB magnet

The idea of MCA is to focus on getting the values of flux passing through air gap between workpiece and steel poles. This flux can be used in Maxwell's pulling force equation to calculate the force on workpiece.

$$F = \frac{-\Phi^2}{2A\mu_0}$$

where, μ_0 is the air-gap permeability.

Magnetic circuit was setup using simple blocks in Simulink. The reluctance and flux sources were oriented to get desired flux direction in different loops.

A MATLAB file was used to programmatically solve the magnetic circuit at different design parameter values and calculate the clamping force.

Force values were obtained by simultaneously varying length of AlNiCo and height of NdFeB. To consider the effect of varying these two parameters on force, a Sensitivity analysis was performed using Sensitivity Analyzer tool in Simulink. Tornado plots were obtained which indicates the influence of selected variables on Force.

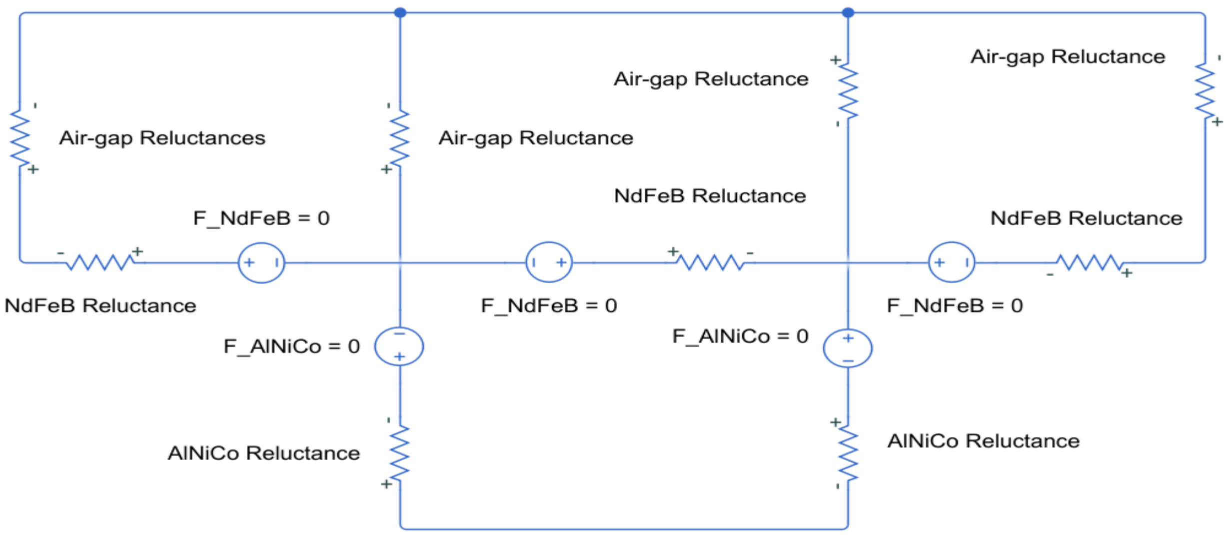

Figure 4- Magnetic Circuit for ON configuration

II.B. Finite Element Method Magnetics (FEMM)

FEMM [1] is a Finite Element Analysis suite used for solving low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. It's straightforward and intuitive interface makes it a great tool to simulate simple to complex electromagnetic circuits quickly.

A planar model of the EPMC with a uniform thickness of 50mm was made using the software. An air gap of 0.1mm was kept between the EPMC and the Workpiece. Due to the lack of 1025 Steel in FEMM library, a 1020 Steel, which has similar properties was used. Since NdFeB magnet is the primary flux source, with AlNiCo magnets acting merely as flux conductors, NdFeB magnet of the greatest BH_{max} value was selected – N52. The results from the sensitivity analysis and MCA, allowed us to identify the crucial design parameters and to narrow down the parametric space to obtain the desired force range. Using FEMM, the force in OFF condition was considered as a major parameter in finalizing the EPMC design.

The force data for various design configurations were obtained by utilizing the integration of FEMM with MATLAB as well as FEMM's LUA scripting. A MATLAB code was written to call the FEMM model of the EPMC, and multiple simulations were carried out by changing the design parameters. The Force in the OFF condition corresponding to each design parameter was observed and the configurations that gave minimal force pulling force was selected. The Forces in ON condition for these configurations were collected and finally, models that gave desired force of around 1500lbs were selected for further optimization and verification using ANSYS Maxwell 3D.

II.C. ANSYS Maxwell 3D analysis

Our analysis in FEMM package was reasonably accurate in that we were able to determine dimensions that would help us to achieve the required objective of force. We were also able to handle saturation effects reasonably well. Although FEMM is a 2D analysis, we can also add depth in the analysis. It has a limitation that the depth remains uniform for the entire device, we cannot give depths to each element individually.

In ANSYS Maxwell 3D analysis, we were able to resolve this issue by creating a 3-D model of EPMC with different depth dimension for each element. In the 3D magnetostatics set-up, we need a CAD model with its respective material assigned. The CAD geometry was mapped by using design variables which were defined beforehand in the *Design Parameters*.

After the geometry is created, we assigned material to each element. ANSYS material library has a range of magnetic materials out of which we have chosen different pairs of **LNG 34, 37, 44, 52** for AlNiCo magnet, & **N32, N37, N52** for NdFeB.

Having created the EPMC total body, a Force result was set-up in OFF configuration. Again, the initial set of dimensions were taken from FEMM's optimum value and the first basic analysis was done. Then we used the following tools available in ANSYS Optimetrics:

II.C.1 *Sensitivity analysis* - Identified which variables or design parameters have more influence on our end objective compared to the rest.

II.C.2. *Parametric sweep* - Performed several design checks using those variables which were proven sensitive for a specified range and tabulated the Force values for different design variable combinations.

We expect Maxwell results to have similar values as that of the values obtained in FEMM analysis since the only thing changing is the depths defined for individual elements.

III Results

After performing analysis using MCA, FEMM and ANSYS Maxwell different results in the form of plots and simulations were obtained.

III.A. Results from MCA

Using MCA, the force is estimated while varying the NdFeB height. The following plot shows the results:

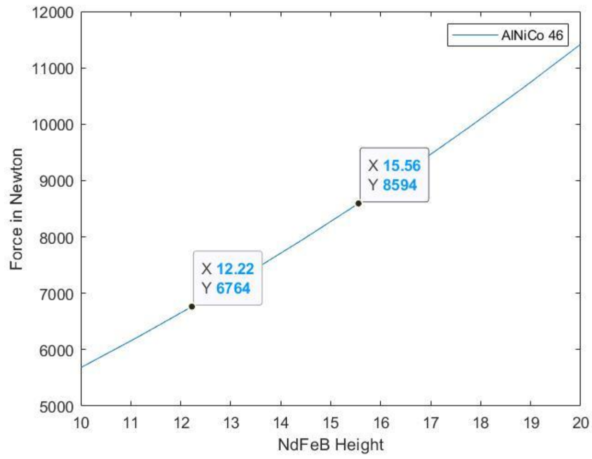

Figure 5 – Force vs NdFeB height results using MCA

Being a 1-D analysis with several assumptions, selecting the optimized parameters from this method was not suitable. So, we decided to take this analysis as a source of information to perform further iterations. Iteration range for different parameters based on MCA.

A sensitivity analysis was done using Simulink. Height of NdFeB, Length of AlNiCo and Case width were selected as parameter lists. Requirement was set based on desired force value (~ 6700 N). The results showed different parameter sets which satisfy these requirements. Extreme values of these parameters were observed from the data to give a suitable range.

Table 2 – Suitable range obtained from MCA

Variable	Range
L_{ny}	12 – 20 mm
L_c	16 – 22 mm

A tornado plot was obtained to check the influence of each variable on force values.

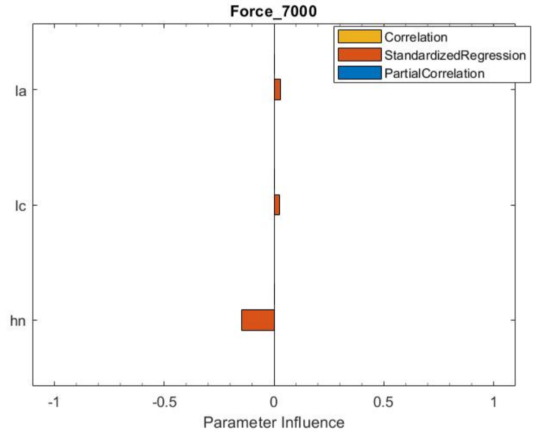

Figure 6 – Tornado plot indicating parameter influence (hn- NdFeB height, la- Length of AlNiCo, lc- Width of casing)

The above results indicate that Height of NdFeB influences the force value more than any other parameter. In further analysis also we observed similar trend of parameter influence on Force values.

MATLAB code and Simulink circuit used is attached in the Appendix.

III.B. Results from FEMM

From the range of NdFeB height obtained from MCA, and assuming that the pole steel height to be greater than the NdFeB, to avoid flux saturation, simulations for the ON condition were carried out by parametric sweeping using nested loop commands in MATLAB.

Figure 7 shows a surface plot obtained by simultaneously varying pole height and NdFeB height in FEMM for OFF condition. The yellow region shows the minimum pulling force, which suggests that the NdFeB height can be kept between 16-20 mm and pole height should be between 20-25 mm. In the above range, minimum force in OFF condition was obtained at 18mm NdFeB height. Variation of the NdFeB position with respect to the pole, and case width, were observed to not have much effect on the force. Hence, the NdFeB was placed centrally, with the center line coincident with the Pole steel, and the case width was fixed to be 20mm.

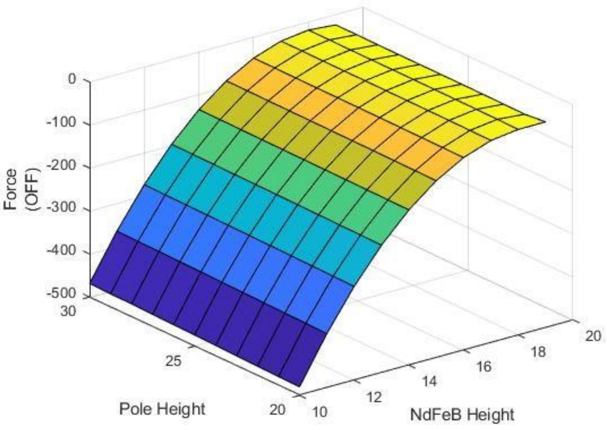

Figure 7 – Surface plot of Force (OFF) vs NdFeB height vs Pole height

Simulations in the ON condition for the range observed in OFF condition were performed and configurations that gave a force having magnitude about 9000 N (more than 1500 lbs) were selected. A much higher force range was selected to address the limitation of all elements having uniform thickness. These parameters are shown the table (xx). Although the EPMC design was optimized, there were a few parameters and assumptions that were inaccurate in FEMM, such as the depth/thickness of the NdFeB, as well as AlNiCo magnets.

Table 3 – Values of Pulling force in ON and OFF condition

NdFeB Height	**Pole Steel Height**	**Force (ON)**	**Force (OFF)**
18	20	-9222	-21.70
18	25	-8840	-19.97

The simulation results in figure 8 shows OFF state where the flux linkage is confined to the EPMC body only and ensuring minimal leakage out of it. In figure 9, the ON state shows maximum flux passing through the work-piece region.

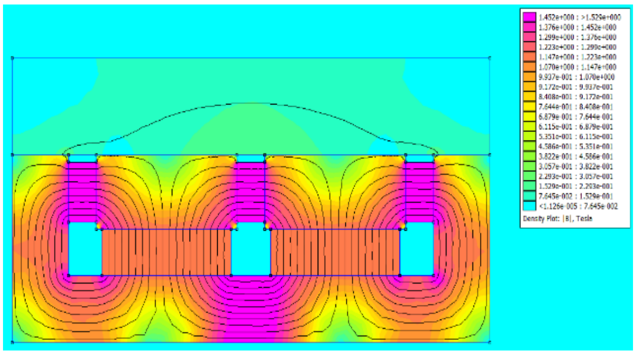

Figure 8 – EPMC in OFF configuration

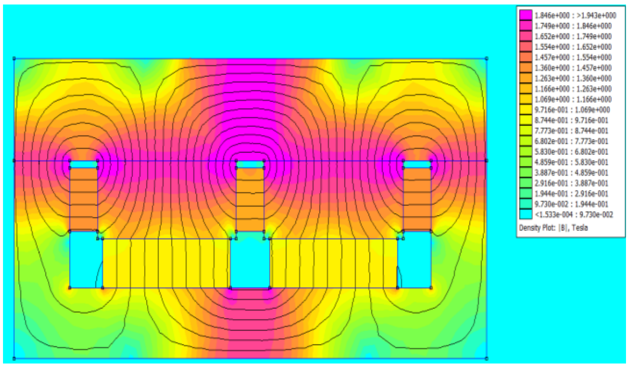

Figure 9 – EPMC in ON configuration

These refined design parameters were used in the ANSYS Maxwell 3D to move towards further optimization.

III.C. Results from ANSYS Maxwell

In ANSYS Maxwell, we obtained good amount of refinement in depth dimensions which was not possible in FEMM analysis.

Using sensitivity analysis in *Optimetrics* toolbox, we discovered that variation in almost all the variables attribute to a change in the reluctance force.

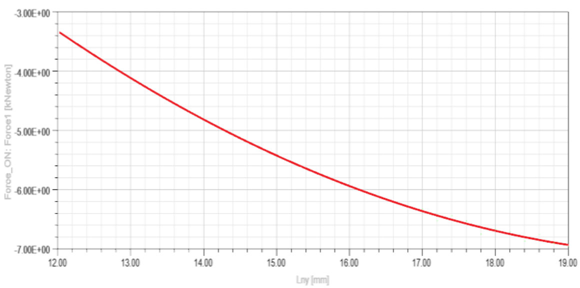

Figure 10 – Force in ON condition vs Lny

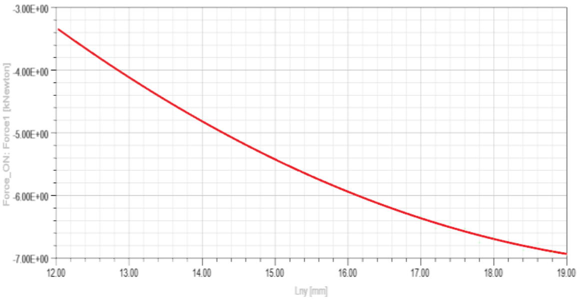

Figure 11 – Force in ON condition vs Lnz

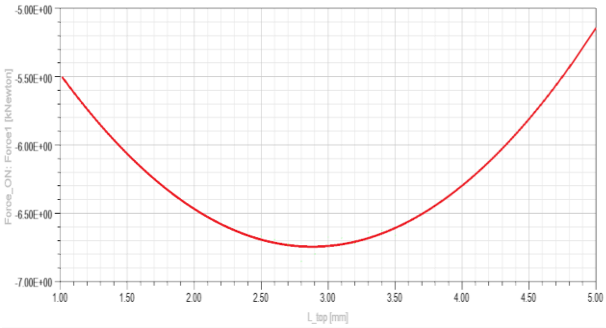

Figure 12 – Force in ON condition vs Ltop

In figure 11, we can see that variation in depth affects the force. This variation was not seen in any other analysis (MCA and FEMM). Two optimum points were obtained from figure 11, 37 mm and 47 mm. Analysis using these dimensions in Maxwell separately showed that force in OFF condition is higher(not desirable) at 37 mm depth, so 47 was selected as NdFeB depth to proceed further with design optimization.

ANSYS *Optimetrics* was used to perform variation in all possible design variables. The range used in *Optimetrics* was taken from the results of FEMM where the OFF force obtained was minimum. These values were taken to get the magnitude of force in ON condition

Table 4- Range used in ANSYS Optimetrics

Variable	Range
L_{ny}	16 – 20 mm
L_{py}	20 – 25 mm

From the data obtained (complete data included in Appendix), the set of dimensions which gave the force value close to 1500 lbs (6675 N) were selected.

Table 5 – Suitable dimensions from Optimetrics data

L_{ny}	L_{py}	Force ON
18	22	6703.34 N
19	21	6822.71 N
20	22	7095.29 N

From the above values, we select the optimum dimension which minimizes the magnet's effective dimensions.
The table of comparison between refined variables values from FEMM and ANSYS Maxwell are shown below:

Table 6 – Comparison of FEMM and Maxwell result

Var.	FEMM Optimum	Maxwell Optimum	% change
L_{ny}	18 mm	18 mm	0
L_{nz}	50 mm	47 mm	-6.39
L_{py}	22 mm	22 mm	0
L_{ay}	14.1 mm	14.1 mm	0
L_{az}	50 mm	46 mm	-8.7
L_c	20 mm	20 mm	0
L_{top}	2.5 mm	2.5 mm	0

The above dimensions are based on the material pair – **LNG 37** & **N52** grade of AlNiCo and NdFeB Permanent magnet respectively [2] [3].
At optimum dimension values force using FEMM and Maxwell were compared. Force values at ON condition are significantly different in both methods.

Table 7 – Force in ON and OFF condition using FEMM and Maxwell

Method	FEMM	Maxwell	% Change
Off State	-20.1	-20.923	3.93
On State	-9096	-6673.7	36.29

Simulation results from ANSYS Maxwell indicating the flux lines are as follows:

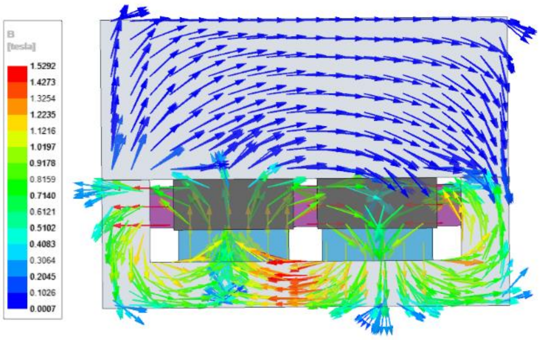

Figure 13- Flux flow lines in OFF configuration

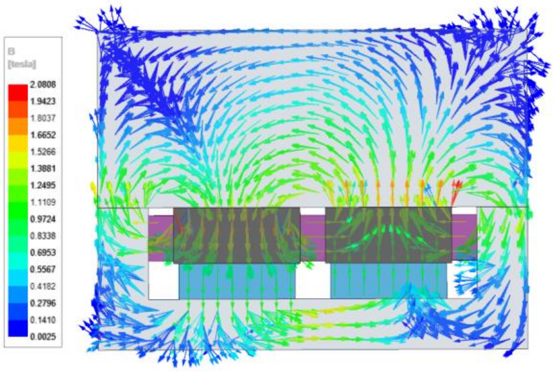

Figure 14 - Flux flow lines in ON configuration

The vector plot validates the flux direction in ON and OFF conditions.

IV Cost Estimation

For cost estimation of EPMC, material is considered as a major factor. To estimate the material cost, first the volume of each material is calculated and then multiplied by its cost per unit volume.

NdFeB and AlNiCo magnets contribute significantly to the material cost. Volume of these magnets and Steel (pole + casing) at optimum dimensions are as follows:

Table 8 – Volume and mass estimation of EPMC components

Material	Volume (in mm^3)	Mass (in kg)
NdFeB (3 unit)	25380	0.1878
AlNiCo (2 unit)	59248	0.4273
Steel (poles+casing)	352000	2.766

Different suppliers provide magnets at different costs. Following are the cost per unit volume calculated from magnets available in the market [4]:

Table 9 – Cost per kg for different materials

Material	Cost per kg
NdFeB N52	$ 77.16
AlNiCo	$ 44.092
Steel	$ 0.7165

The estimated cost of material used in EPMC:

Material	Cost
NdFeB	14.49 $
AlNiCo	18.84 $
Steel	1.98 $
Total	**35.31 $**

This is a basic estimation of material cost in EPMC.

V Conclusion

The project posed a challenging design optimization task where the objective itself was a constraint. We began by evaluating electrically analogous magnetic circuit and obtain our first trial variables. We also learned the influence of each variable and parameter on the design objective. This provided an idea of the bandwidth of the feasible design space. The information was then taken onto a 2D analysis scheme in FEMM where greater amount of convergence towards result was obtained using automated LUA script. The design solution was tested for validity with Maxwell's superior capabilities and some more dimension-cutting was achieved. To understand how the local design variables affect the design, sensitivity analysis proved out to be a great tool and shaped most of our design optimization.

Our final aim was to minimize the overall volume of the EPMC device which would directly minimize the total material cost. Through survey, we learned that magnets have a narrow range of cost variation for different grades. Hence, performed a preliminary cost estimation based on the readily available cost values and final design parameters.

VI References

1. FEMM user manual - http://www.femm.info/Archives/doc/manual34.pdf
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