Research Article

Finite Element Analysis of Electromagnetic Clutch

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Abstract

Electromagnetic clutch, are systems used in many applications like packaging machines, wire tensioning units, printing machines, etc. The main components of electromagnetic clutch are coil, lining, body, armature, and rotor pulley. It becomes active when the system gives DC electric current to the coil. The magnetized body exerts an attraction force on the armature and transmits torque depending on the friction coefficient of the lining. In this study, magnetic and structural analyzes of electromagnetic clutch is commercially used with a torque of 7 Nm were performed with a finite element-based Ansys software. As a result of the study, tensile forces, torque values, magnetic flux density were obtained. The results were analyzed and data were created for future studies.

Keywords: Clutch, Electromagnetic, FEM

1. Introduction

1.1 What is Electromagnetic Field?

Magnetic fields and electric fields are related to electric charges. According to the observer, if the charged particles are stationary, there is only one electric field. If the charges are moving, the observer will feel the effects of the magnetic field as well as the electric field caused by the motion of the charged particles. Faraday and Maxwell formulated these phenomena to prove that they are affected by the motion of charges, which interests observers, and that a time-varying magnetic field creates an electric field, and at the same time, a time-varying electric field creates a magnetic area. The

electromagnetic field is the primary state of the magnetic field along with the electric field (Yıldız, 2013).
Electromagnetic field principles, packaging machines, wire tensioning units, printing machines, brake systems, etc. are used in many applications. The magnetic field, which has a wide usage area, is expressed as shown in equation (1,1) below(Akyazı, 2006).

$$\Phi_B = \int B.dS \tag{1.1}$$

Here Φ_B denotes magnetic flux. A force is created when a charge q enters the magnetic field B with velocity υ. This force;

$$\vec{F} = q(\vec{\upsilon} x \vec{B}) \tag{1.2}$$

The magnetic force of the conductive wire, up to dl, on which current is flowing;

$$dF = i.dlxB \tag{1.3}$$

1.2 Electromagnetic Clutch

Electromagnetic clutches, which are among the magnetic field applications mentioned above and which are the subject of this study, are systems that work with the magnetic field principle and transmit torque mechanically. For this reason, they are referred to as electromechanical clutches(Sanjulal, Baby, Vishnu, & Kumar, 2016). Today, electromagnetic concepts: friction electromagnetic clutch, electromagnetic jaw assembly clutch, magnetic powder clutch, and slip-type electromagnetic clutches are available(Yin, Qi, & Qu). The electromagnetic clutch is best suited for remote starting as it does not require a connection to control its engagement. It has a very fast and smooth operation feature. However, there is a possibility of the clutch overheating as energy is dissipated as heat in the electromagnetic actuator each time the clutch engages. As a result, the maximum operating temperature of the clutch is limited by the temperature rating of the electromagnet insulation(Sanjulal et al., 2016).

The main components of Electromagnetic Clutches are coil, lining, body, armature, and rotor pulley.

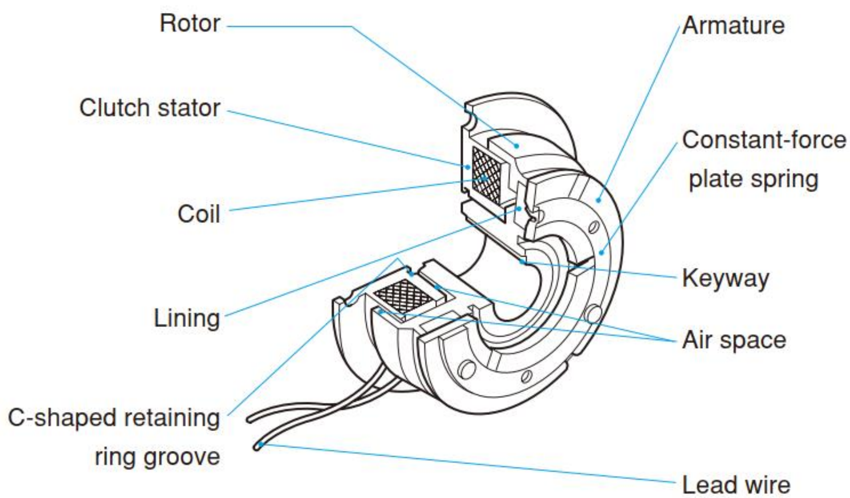

Figure1.1 Main Components of Electromagnetic Clutch (https://www.mikipulley.co.jp/EN/Products/ElectoromagneticClutchesAndBrakes/about.html)

1.3 Literature research

There have been many academic studies on electromagnetic theory and especially on industrial products, which are the technology of this theory. Some of the studies on this subject are summarized here. Let's start with the work done by Chowdhary, Abhishek, Anupam Kumar, and Sanket Kumar Singh. In the studies, the design and analysis of the Electromagnetic Coupling were investigated by the authors. The engagement and disengagement of the clutch are provided electrically, but the torque is transmitted mechanically. It has been investigated that it overcomes the problem of high response time that occurs in mechanical clutches(Chowdhary, Kumar, & Singh, 2020). Yet another study is aimed at the automotive sector. This study was done by Kunii and Rikiya. In the study, the SH-AWD (Super Drive-All-Wheel Drive) system, which is the world's first 4WD system that can continuously and variably distribute torque to all four wheels of the vehicle, was developed. The use of this system allows the control application of torque in controlling the yaw moment and equalizing the load ratio between all wheels of the vehicle(Kunii et al., 2005). In 2010, Piao et al. carried out an important study on electromagnetic coupling. In this study, the static friction torque of electromagnetic clutch was investigated by Piao and Chang Hao. Torque maximization was also investigated by optimizing the geometric shape of the armature. It has been noted that estimating torque is a very important factor in designing and optimizing the electromagnetic clutch. An axis-symmetric FEM model was created to analyze the static friction torque and a torque tester was used to evaluate the actual torque(Piao, Huang, Wang, & Cho, 2010). Another study on electromagnetic coupling was carried out by Fernando et al. in 2016. In this study, Fernando and Nuwantha presented the control of an electromagnetic clutch. The clutch under consideration is based specifically on the modulated field principle and has two shafts with a speed ratio of 1.14 in synchronous conditions. Clutch, disengagement, and torque transfer are stated to be controlled by manipulating the stator currents and the slip rate between two shafts. It has been found that the dynamic pattern of the electromagnetic clutch is almost identical to that of a permanent magnet synchronous machine(Fernando, 2016). The study for the automotive sector was carried out by Muramatsu et al. In this study by Muramatsu and Junya, a device for electromagnetic (EM) coupling that suppresses the overvoltage produced by turning off a vehicle's ignition is investigated. Through the theoretical consideration of the EM field, it has been found that a larger eddy current in the EM clutch can suppress the overvoltage as it causes a small time change in the magnetic flux through the coil(Muramatsu et al., 2014). A study was carried out by Uçar on Maxwell's equations. Uçar made a study on Maxwell's Field Equations. Maxwell showed with his field equations that electricity and magnetism, which were thought to be two separate phenomena, are two separate components of a single phenomenon. Maxwell not only developed the basic equations of electromagnetism but also used these equations to predict the existence of electromagnetic waves and to show that light is an electromagnetic wave. In this study, the emergence and effects of Maxwell's field equations were investigated by using data from the history of physics(Semra, 2019). Another type of clutch, which is one of the magnetic clutch types, is the particle-based clutch. On this product, the working principle of magnetic particle coupling was analyzed in depth by Xu Shenzhen and Cheng Wang in 2011, and the electromagnetic field, which is an analysis model of magnetic coupling, was created. The finite Element Method and experimental verification of electromagnetic field in magnetic particle coupling have been completed. Test results are analyzed, showing that the simulation method and theory are reasonable and can be used as the basis for grip optimization(Xu & Wang, 2011). One of the good applications of the electromagnetic clutch was made by Chen Q et al. and parking brake design was realized with this theory. In this study by Chen Q et al., he presents the parking brake design, which is an electromagnetic clutch embedded in the in-wheel motor. Magnetic heat characteristics and heat dissipation characteristics were the main factors affecting electromagnetic clutch performance. They argued that the working principle of the electromagnetic clutch is to produce electromagnetic suction under electromagnetic induction(Chen, Shu, Chen, Tu, & Liao, 2016). Another application in the automotive sector was made by Ranjan et al. In their study, Ranjan and Ashish say there is a growing interest in the Automatic Transmission in India as it provides better comfort and sustainability, but the high cost of this system has limited it to be successful in Indian markets. For this reason, Automated Manual

Transmission (AMT) was considered, which offers a better solution to automation as it improves the driving ability and fuel consumption characteristics of the manual transmission at lower costs. However, torque lag and comfort are major issues that can be addressed by reducing shift time with AMT(Ranjan, Prasanth, Cherian, & Baskar, 2017). A thesis study on the importance and use of electromagnetic clutches was made by Dandi in 2019. Dandi, Working, in his thesis study, the clutch is a device used to connect or disconnect the engine torque from the transmission depending on the driver's request. He emphasized that the current friction clutch system has many disadvantages. He said that mechanical force is required that can cause torque relaxation. In addition, direct contact with mechanical parts increases the likelihood of component failure and mechanical noise. This thesis proposes the new Electromagnetic clutch (EMC) system, which replaces the existing friction clutch system(Dandi, 2019).

As can be seen from the literature research, electromagnetic theory-based technological products have been developed in many sectors and scientific research has been carried out on this subject. Especially today, with the development of computer-aided design (CAD) and computer-aided engineering (CAE) technologies, progress has been made for more accurate and effective designs of products. In this context, geometric optimization, topology optimization, and finally generative design technologies have emerged. In this study, the geometric optimization of a part of electromagnetic clutches, which should be included in the literature and which is an important product for technological products, is emphasized.

2. Materials and Methods

In this study, we will use the Finite Element Analysis (FEM) method. Finite element analysis is a numerical modeling technique developed for the analysis of engineering problems with complex geometry and nonlinear materials(Dietrich, Chabu, & Cardoso, 2001). It is especially applied in solving two or three-dimensional partial differential equations and boundary value problems. FEM essentially divides a large system into smaller components, which are finite elements(Jin, 2015).

Problem geometry is decomposed by mesh structures; Points called nodes are created on the volume or surface. Each node is assigned its own material properties. By taking advantage of its periodicity and symmetric properties, the dimensions of the problem can be reduced by using boundary conditions(Gülbahçe, 2013).

Analysis studies are carried out faster thanks to computer-aided engineering software. In this study, it will be done with ANSYS, which is very powerful in analysis. There are many modules in ANSYS software. This study will be done with Ansys Maxwell. Ansys

Maxwell is powerful software for the analysis and design of electromagnetic and electromechanical instruments.

Maxwell's equations, together with the Lorentz force laws, consist of four equations that form the source of classical electrodynamics, classical optics, and electrical circuits and explain electromagnetic phenomena. The integral forms and derivative expressions of these four equations are given in Table 2.1 below.

Table 2.1 Maxwell Equations

Integral Forms	Derivative Expressions	Explanation
$\int \mathrm{E.dA} = \frac{\mathrm{Q}}{\varepsilon_0}$	$\nabla.\mathrm{E} = \frac{\rho}{\varepsilon_0}$	(Coulomb's Law)
$\int \mathrm{B.dA} = 0$	$\nabla.\mathrm{B} = 0$	(No Magnetic Charge)
$\int \mathrm{E.dS} = -\frac{\mathrm{d}\Phi_\mathrm{m}}{\mathrm{dt}}$	$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}}$	(Faraday's Law of Induction)
$\int \mathrm{E.dS} = \mu_0 \mathrm{I} + \varepsilon_0 \frac{\mathrm{d}\Phi_\mathrm{m}}{\mathrm{dt}}$	$\nabla \times \mathrm{B} = \mu_0 (\mathrm{J} + \varepsilon_0 \frac{\partial \mathrm{B}}{\partial \mathrm{t}})$	(Maxwell's Ampere Law with Displacement Current)

2.1.Taguchi Method

Taguchi's techniques have been widely used in engineering design. The Taguchi method includes system design, parameter design, and tolerance design procedures to achieve a robust process and result in the best product quality. The core reliance of Taguchi's techniques is the use of parameter design, an engineering method for product or process design that focuses on identifying parameter (factor) settings that produce the best levels of a quality attribute. Taguchi designs provide a powerful and efficient method for designing processes that operate consistently and optimally in a variety of conditions. Determine the best design requires the use of a strategically designed experiment that exposes the process to various levels of design parameters(Karna & Sahai, 2012).

Experimental design methods were developed in the early years of the 20th century and have since been extensively studied by statisticians, but were not easy to use by practitioners. Taguchi's approach to experimental design is easy to adopt and implement for users with limited knowledge of statistics; therefore, it has gained wide popularity in the engineering and scientific community. Taguchi noted three situations:(Gökçe & Taşgetiren, 2009).

●When the result, called the performance characteristic, is the lowest best:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (2.1.1)$$

●When the highest (large) is the best:

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{y_i^2}\right) \qquad (2.1.2)$$

●When nominal is best:

$$S/N = -10\log\left(\frac{\bar{y}^2}{s^2}\right) \qquad (2.1.3)$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \qquad (2.1.4)$$

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2 \qquad (2.1.5)$$

Here y_i= Performance characteristic, i= observation value, n= number of tests in trial, $\bar{y}$ = Average of observation values, S^2=Variance of observation values. The larger the S/N ratio, the smaller the product variance around the target.

2.2. Experimental Design

Taguchi method was used as the experimental design method. As the number of parameters and levels increase in experimental designs, the number of experiments will also increase. Optimum results are obtained with less experimentation with the Taguchi method. In this study, 3 parameters and 3 levels were determined. For the experimental design, the experimental design was prepared using the L9 orthogonal array. Minitab program was used while preparing the experimental design. An experimental design was prepared using the L9 orthogonal array. Factors and levels are given in Table 2.2.1. The test list is given in Table 2.2.2.

Table 2.2.1 Experiment factors and levels

Parameters	Level 1	Level 2	Level 3
A: Rotor Material	St 1008	St 1010	S275
B: Rotor Plate Thickness (mm)	2,5	2	3
C: Number of Rotor Plate Holes	12	16	20

Table 2.2.2 Taguchi test table L9

FACTORS		
A	B	C
1	1	1
1	2	2
1	3	3
2	1	2
2	2	3
2	3	1
3	1	3
3	2	1
3	3	2

After the experimental design was prepared, the model designs were simplified and prepared in accordance with the analysis. The three test factors (material, plate thickness, and the number of holes on the plate) that we will apply to the rotor are modeled as solid models.

Maxwell was used for electromagnetic analysis. In Maxwell hardware, the coil is carefully selected in Amps/Torns (A/T). Coil as 250 A/T. Material of tensioning according to engineering design as st1008, st1010, and steel for the rotor. B-H curves for st1008, st1010, and steel are given in figure 2.2.1.

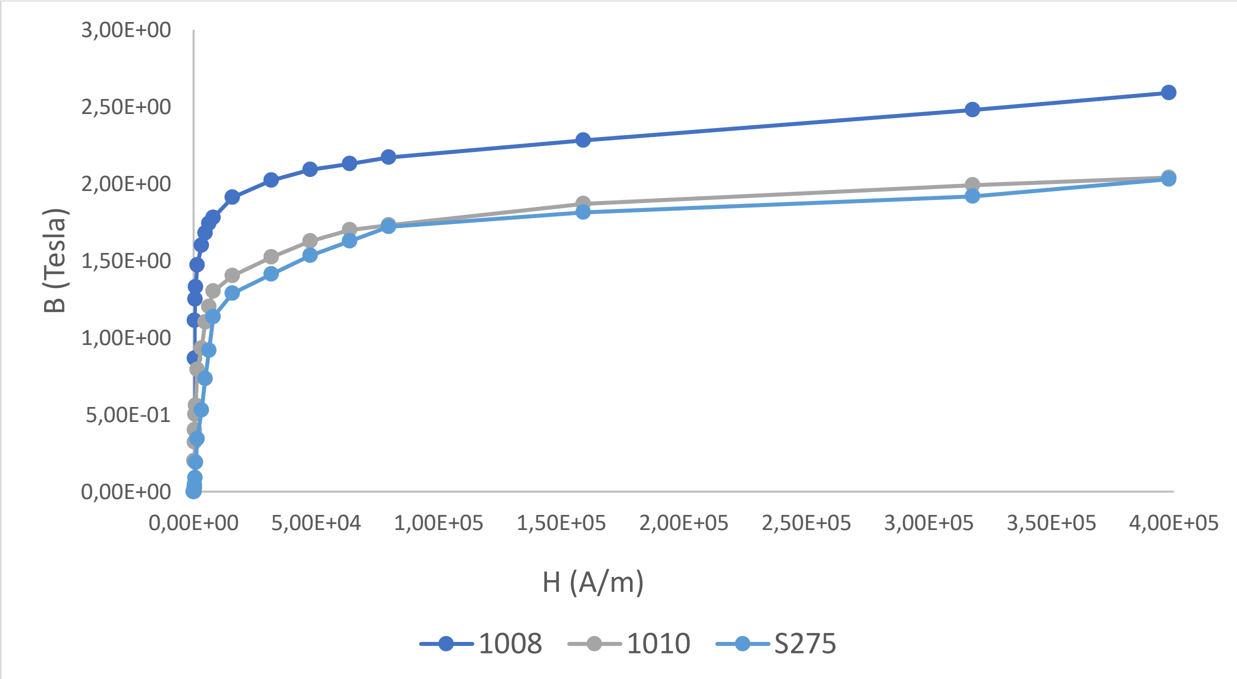

Figure 2.2.1 B/H curves for materials 1008, 1010, and S275 [Ansys]

3. Research Results and Discussion

X The results of the studies prepared with Taguchi experimental design and finite element analysis are shared in this section. With the electromagnetic simulation performed in the study, the grip pulling force was calculated. The clutch torque value was calculated in the Nm unit by using the friction element inner diameter and outer diameter, and the friction coefficient from the calculated clutch pulling force. The clutch friction coefficient was taken as 0.55 from the manufacturer's catalog. The torque values obtained according to the L9 test table are given in Table 3.1. Again, the calculated S/N ratios are given in the table.

Table 3.1 Torque Values

#	A	B	C	Tork [Nm]	S/N
1	1	1	1	5,10	14,15
2	1	2	2	3,40	10,62
3	1	3	3	12,00	21,58
4	2	1	2	7,00	16,90
5	2	2	3	4,30	12,66
6	2	3	1	3,40	10,62
7	3	1	3	13,00	22,27
8	3	2	1	2,90	09,24
9	3	3	2	6,20	15,84

S/N ratios and torque values calculated with the largest is the best approach were obtained, and the largest 13 Nm and the smallest 2.9 Nm torque values were obtained in these values. As a result of the study, the magnetic flux density distribution of the 7th experiment, which gives a torque value of 13 Nm, and the flux density vectors in the 3d case is given in Figure 3.1 and Figure 3.2, respectively.

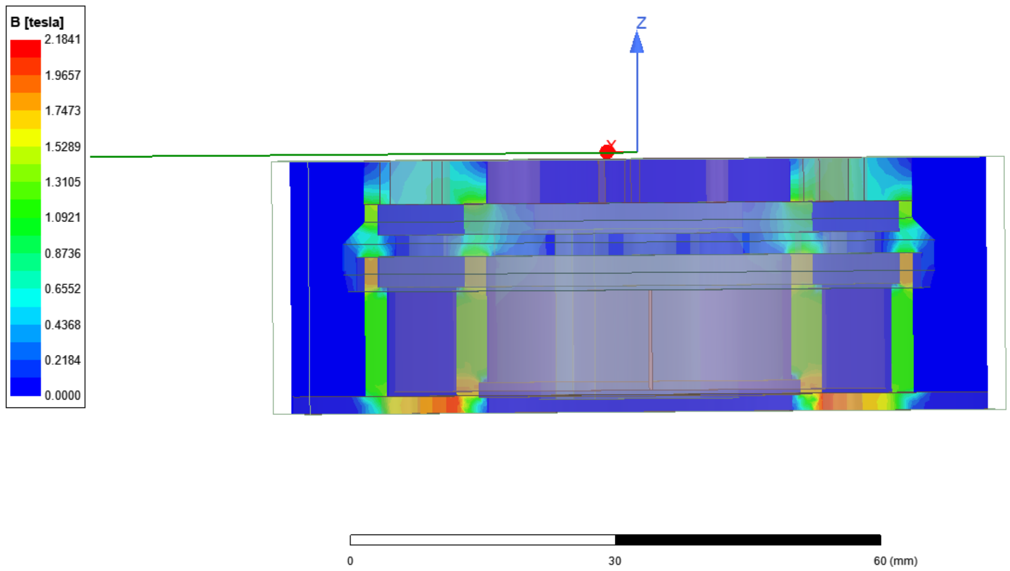

Figure 3.1 Magnetic flux density distribution

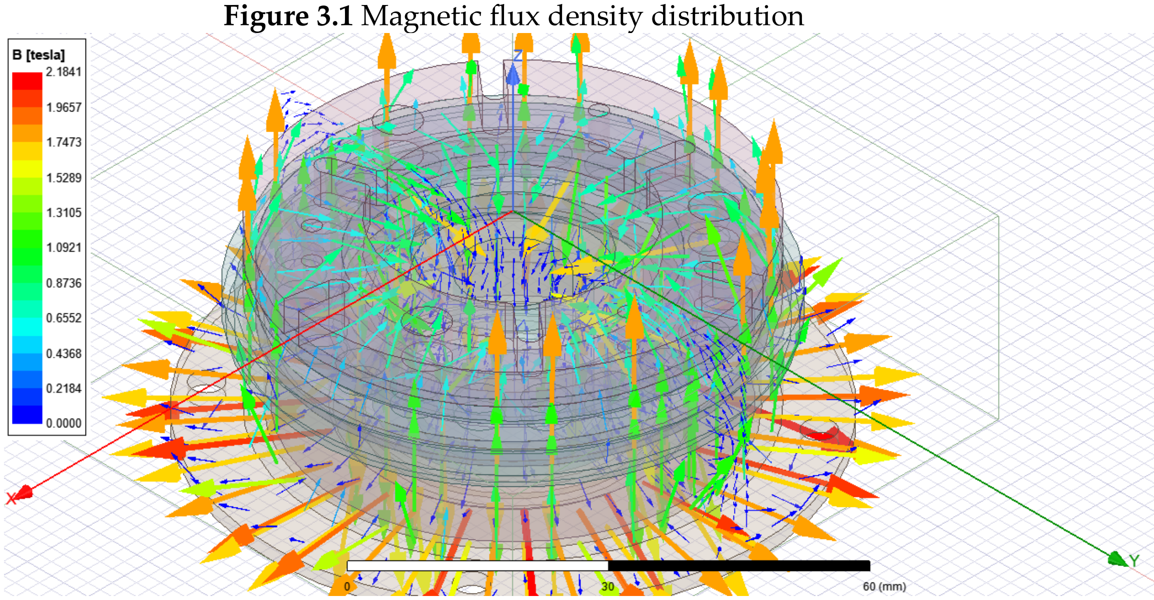

Figure 3.2 Magnetic flux density vectorial

In the study, the smallest torque value of 2.9 Nm was obtained at 8 th experiment. The 3d magnetic flux density vectors and the magnetic flux density distribution contour plot of the experiment with the worst result are given in Figure 3.3 and Figure 3.4, respectively.

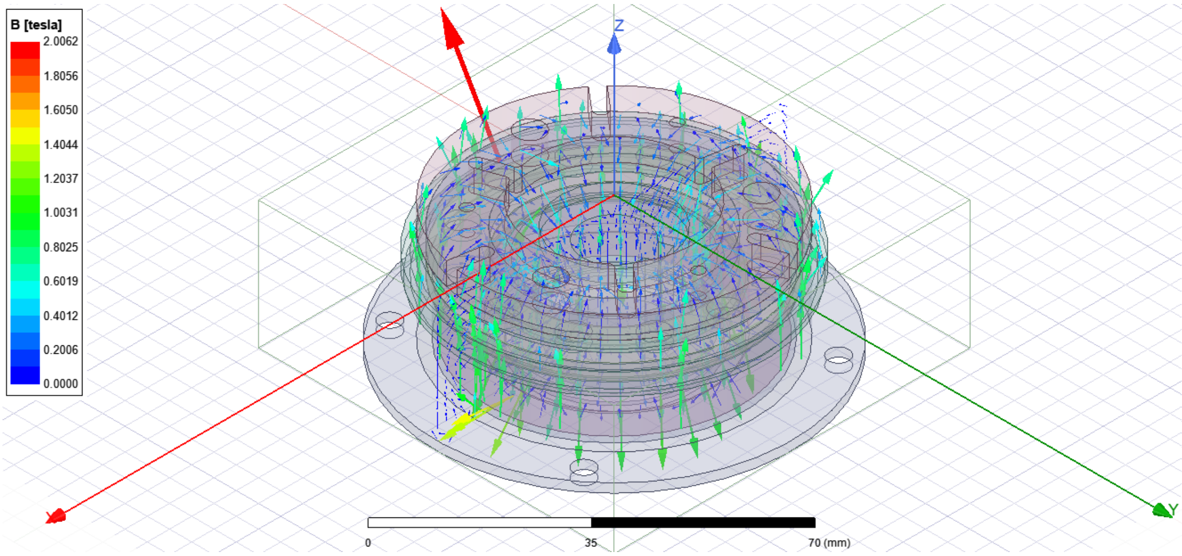

Figure 3.3 Vectorial magnetic flux density

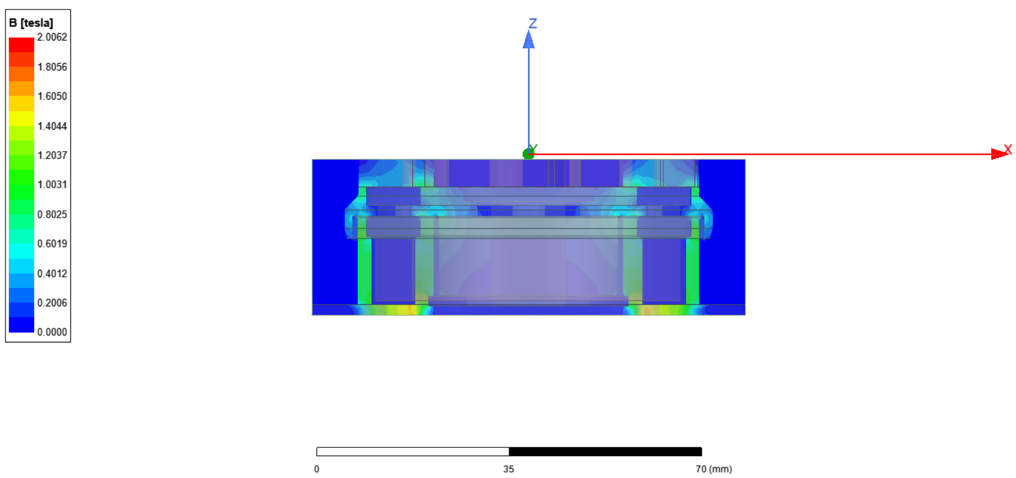

Figure 3.4 Magnetic flux density distribution

S/N ratios were calculated for each experimental parameter in the Taguchi analysis performed on the L9 test table. S/N calculations made with the largest-best approach are aimed at detecting the experiment with a strong signal ratio. With this approach, the experimental study signal/noise ratios were calculated. Afterward, when the full factorial experimental design is made, 27 experiments that should be done were estimated with the Taguchi experimental design estimation formulation. Signal/noise ratios for the factors are given in Figure 3.5 and estimated torque values are given in Figure 3.6.

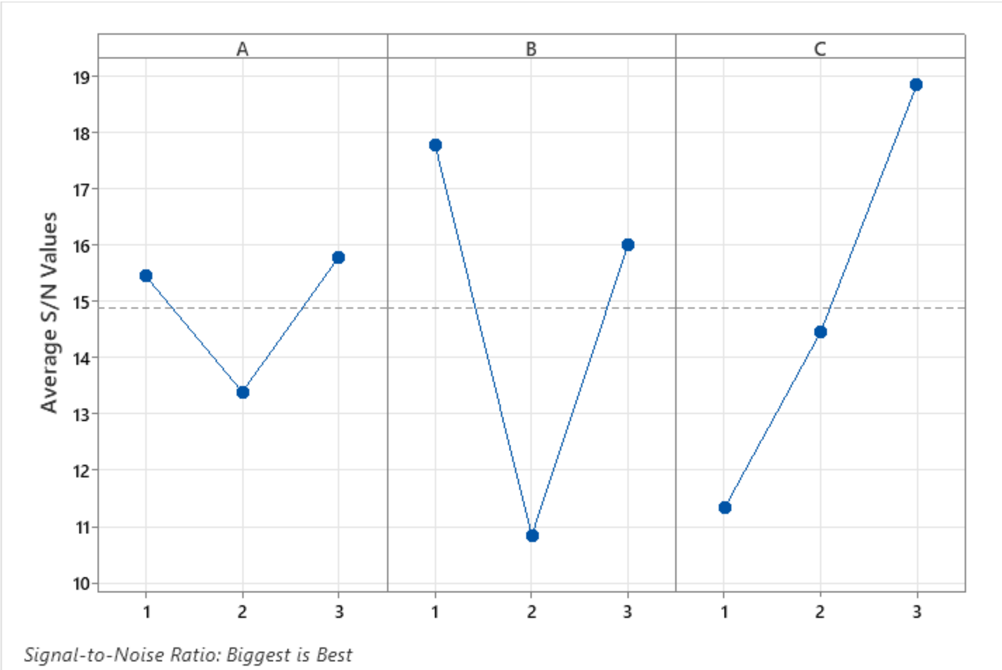

Figure 3.5 Signal-to-noise ratios for test factors

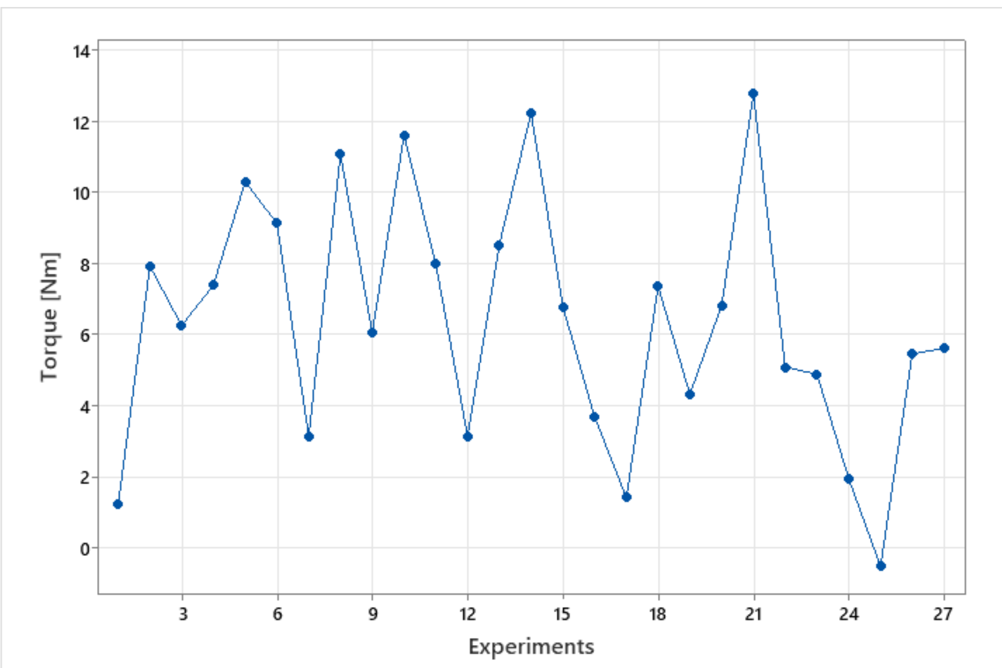

Figure 3.6 Torque values for test factors

4. Conclusion

In this study, a simulation study was carried out on the electromagnetic theory-based electromagnetic concept, which is the theory behind many technological products. In the simulation study, as experimental design parameters, the materials of the clutch elements, the thickness of the rotor material, which is the most important component affecting the clutch attraction force, and the number of holes on it were optimized. Taguchi experimental design method, one of the statistical experimental design methods, was used in the study. In the study, 3 parameters and 3 levels for each parameter were used. While 27 experiments are required in full factorial experimental design, the L9 experimental design table was used considering both time and cost factors. CAD models of the products were prepared according to the L9 experimental design table, which is a 1/3 fractional test table, and tensile forces were obtained for each test by applying material assignments and necessary electromagnetic simulation steps. The clutch torque value (Nm) was calculated by using the friction coefficient and geometry dimensions of the lining for each test using the pulling forces. After the Taguchi analysis, S/N ratios were calculated for each experiment and the optimal parameters were tried to be determined. 27 experiments, the number of full factorial experimental designs, were estimated and the results were graphed.

When the results were examined in the study, it was observed that the torque values obtained as a result of the simulation varied between 2.9 Nm and 13 Nm torque values. For the experiments giving the highest and lowest torque values, the magnetic flux density was examined as a contour plot in 2d and a vector plot in 3d. As can be seen from the graphs, it was observed that the magnetic flux density was low in the experiment, which gave a low torque value, and therefore the pulling force was low. In Table 4.1 given below, the parameters for the experiments that give the lowest and highest torque values are given. As can be seen from the table, for the worst test case, General Structural Steel material, 2mm rotor thickness, and 12 holes are seen. For the best case, there is again General Structural Steel material, 2.5mm rotor thickness, and 20 holes. When the results are examined, it is seen that the most effective parameter is the number of holes. It is seen that with the increase in the number of holes used in the product, the magnetic flux from the rotor component passes easily and attracts the armature plate more.

#	A	B	C	Torque [Nm]	S/N
7	General Structural Steel (S275)	2.5	20	13,00	22,27
8	General Structural Steel (S275)	2	12	2,90	9,24

The expected torque value for the product to be developed will be 7Nm. However, due to the heating problem, which is the most important problem in electromagnetic systems, the pulling force decreases depending on the increasing temperature. Due to this decrease, it is necessary to develop products with an average safety factor of 1.4-1.7. When the results were analyzed in this respect, it was seen that the 5th, 8th, and 10th experiments were in the range of 10 Nm to 12 Nm among the results given in Figure 4.6. In the study, the optimal parameters can be ordered to be between these values.

In future studies, the body, armature, rotor, coil, and other design parameters, which are the other parts of the electromagnetic clutc, are made variable, and simulations with a higher-level experimental design method are made, estimations are made with higher-order estimation methods, and factor effects are observed in more detail. Performing Analysis of Variance (ANOVA) and thus determining the optimal parameters can be performed.

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