

USING TAGUCHI METHOD TO ANALYSE THE DESIGN PARAMETERS OF A DISC TYPE OF MAGNETIC CIRCUIT

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Abstract

This study investigated the effects of coil wire diameter (d), disc thickness (w), and holding gap (x_i) on the response times and energy consumption of a flat-faced disc type of magnetic circuit. The design of experiment (DoE) was created using the Taguchi L18 orthogonal array approach, with two levels for x_i and three levels for d and w . Then, for each configuration in the DoE, the opening time (t_o), the energy consumption (E_o), and the closing time (t_c) of the magnetic circuit were determined using the MATLAB/Simulink model validated with test data. Signal-to-noise (S/N) analysis was applied according to the smaller-the-better performance criterion to obtain the optimal parameter combination and priority order that would individually minimize t_o , t_c , and E_o . The percentage contribution of each parameter was also evaluated using the variance analysis (ANOVA). In all cases, the most effective parameter was found to be wire diameter (d), and the optimal combinations for each target differed from one another. Therefore, grey relational analysis (GRA) was applied to the DoE results to derive the optimal combination for multiple requirements.

(Received in October 2025, accepted in January 2026. This paper was with the author 1 week for 1 revision.)

Key Words: Flat-Faced Disc Type of Magnetic Circuit, Coil Wire Diameter, Holding Gap, Disc Thickness, S/N Analysis, ANOVA

1. INTRODUCTION

Magnetic circuits are one of the most important elements in mechatronic systems, particularly with technological advancements. They are widely used to transform an electrical signal into mechanical movement. If the mechanical motion is angular, the device is called an electric motor, whereas if it is linear, it is referred to as a solenoid or an electromagnet. Since electromagnets work as actuators in mechatronic systems, their response time must be as short as possible. Therefore, magnetic circuit parameters must be considered to achieve a fast response in the design of these actuators [1-6].

Magnetic circuits are inherently complex, and their fundamental equations are nonlinear due to leakage losses, magnetic saturation, and eddy current effects. Modelling these circuits enables the investigation of their nonlinear dynamic characteristics. There are studies focused on the design, modelling, and application of electromagnets for various engineering fields in the literature [1, 3, 4, 7].

The effects of design parameters on the dynamic behaviour of magnetic circuits can be analysed using analytical or numerical models. Moreover, these effects can also be investigated through the use of experimental or simulation-based data [8]. However, as the number of parameters and their levels increases, the required number of experiments increases. To reduce the number of experiments, the design of experiment (DoE) method can be utilized [9]. In recent years, the DoE using Taguchi orthogonal arrays has become a widely used method [10, 11]. Taguchi-based DoE applications are also available for electromechanical systems [7, 8, 12-19]. Based on the results obtained according to the DoE, the most suitable combination and the order of importance of the parameters are determined by applying S/N analysis [8, 9-11, 15, 16, 19]. Nevertheless, this approach is performed for a single objective function. For multiple objectives, Taguchi-based grey relational analysis (GRA) is employed to identify the overall optimal combination [20, 21].

In this study, a flat-faced disc type of magnetic circuit designed for an automotive application was considered. Initially, preliminary tests were performed on the magnetic circuit without a return spring to investigate the design parameters. Magnetic circuits typically operate against a spring force and are designed to overcome it. Therefore, a MATLAB/Simulink model was employed in this study to account for the spring effect, and the model results were validated with experimental data. Within the scope of the study, the effects of coil wire diameter (d), holding gap (x_i), and disc thickness (w) on the dynamic behaviour and energy consumption of the disc type of magnetic circuit were examined. The DoE was created with the Taguchi L18 orthogonal array approach according to the specified levels of these parameters, and each combination of the DoE was simulated using the MATLAB/Simulink model to evaluate the opening time (t_o), energy consumption (E_o), and closing time (t_c). Afterwards, signal-to-noise ratio (S/N) analysis was applied according to the smaller-the-better performance characteristic in order to minimize t_o , E_o , and t_c , and to identify the optimal parameter combination along with the priority order of the parameters. The contribution ratios of design parameters were obtained using variance analysis (ANOVA). However, the optimal design combinations for each of the three targets were found to differ from one another. So, Taguchi-based grey relational analysis (GRA) was then applied to identify the optimal combinations for multiple objectives.

2. MATERIALS AND METHOD

2.1 Magnetic circuit

This study focuses on a flat-faced disc type of magnetic circuit designed for an automotive application (Fig. 1). The moving element of this magnetic circuit is a disc and has two operating gaps that are magnetically in series and mechanically in parallel. Due to this structure, high magnetic forces are achieved at small air gaps, decreasing significantly as the air gap increases. Furthermore, the magnetic force increases as the current increases [1-4].

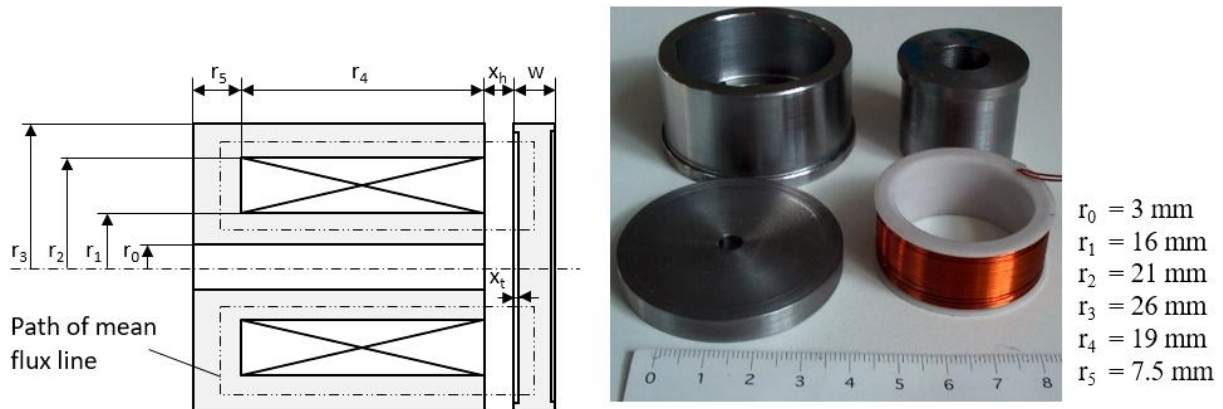


Figure 1: Flat-faced disc type of magnetic circuit.

A flat-faced disc type of magnetic circuit is designed to provide the force required to attract a disc across an air gap. After determining the inner pole radius (r_1) based on the magnetic force, the other dimensions given in Fig. 1 are calculated using Eqs. (1) and (2) [22]. The dimensions of the magnetic circuit in this study are given in Fig. 1. Based on these dimensions, the mean flux line was determined. The coil dimensions and, consequently, the coil wire diameter were selected by considering r_1 , r_2 , and r_4 .

$$3 < \frac{r_4}{r_2 - r_1} < 4 \quad (1)$$

$$r_1^2 - r_0^2 = r_3^2 - r_2^2 = 2r_1r_5 \quad (2)$$

2.2 Modelling of the magnetic circuit

The static and dynamic behaviours of the disc type of magnetic circuit are governed by the interaction of electromagnetic and mechanical principles. In practice, the primary electromechanical relationships include the electrical circuit, the magnetic circuit, and the force equations, which are expressed as follows:

Electrical circuit equation: Based on Kirchoff's voltage law, the equation is expressed as:

$$e(t) = Ri(\phi, x) + N \frac{d\phi(x, i)}{dt} \quad (3)$$

where e is the input voltage (V), R is the coil resistance (Ω), i is the current through the coil (A), N is the number of turns, ϕ is the effective flux of the magnetic circuit (Wb).

Magnetic circuit equation: The magnetic circuit equation, based on Ampere's law, is expressed as:

$$Ni(\phi, x) = \frac{2B_g(x, i)(x_h + x_t - x)}{\mu} + \sum_i H_i l_i \quad (4)$$

where Ni is the magnetomotive force (A-turns), B_g is the magnetic flux density in the air gap (Wb/m²), μ is the permeability of the air gap (H/m), H_i is the magnetic field intensity along the flux line (A-turns/m) and l_i is the length of the flux line (m), x_h is the holding gap (m), x_t is the traveling gap (m) and x is the displacement of the disc (m).

Force equation: The magnetic force resulting from the magnetic flux can be expressed as:

$$F_m(\phi_g, i) = \frac{\phi_g(x, i)^2}{\mu} = \frac{B_g(x, i)^2 A}{\mu} \quad (5)$$

where ϕ_g is the magnetic flux of the air gap (Wb) and A is the effective area of the magnetic circuit (m²).

The force can alternatively be formulated as a function of the air gap and the current as follows:

$$F_m(i, x) = \frac{\mu A (Ni)^2}{4(x_h + x_t - x)^2} \quad (6)$$

Mechanical equation: Using Newton's second law, the motion of the disc can be described by the following equation:

$$F_m = m \frac{d^2 x}{dt^2} + b \frac{dx}{dt} + kx \quad (7)$$

where m is the mass of the disc (kg), b is the damping coefficient (N/(m/s)) and k is the spring coefficient (N/m).

The block diagram of the Simulink model developed using Eqs. (3) to (7) and the magnetic circuit permeance equations, is given in Fig. 2 [1]. Using this model, the current and displacement, and thus opening and closing times, magnetic force, and energy consumption for the magnetic circuit given in Fig. 1 were obtained.

2.3 Preliminary tests on the magnetic circuit

In this study, the parameters affecting the dynamic behaviour of the flat-faced disc type of magnetic circuit were determined as holding gap (x_t), coil wire diameter (d), and disc thickness (w). Preliminary tests were carried out on the magnetic circuit designed for an automotive application (Fig. 1) using the experimental setup shown in Fig. 3.

After dimensioning the magnetic circuit, the available volume for the coil winding is determined. The coil wire diameter is selected based on the cross-sectional area of this volume. When the coil wire diameter is small, the number of turns increases; however, the coil resistance also rises, resulting the current to increase more slowly. Conversely, the number of turns decreases with the larger coil wire diameter, leading to lower coil resistance and a faster current

rise. Because the number of turns and current affect the magnetomotive force, they directly affect the dynamic behaviour of the system. Furthermore, the energy consumption also varies depending on the current change.

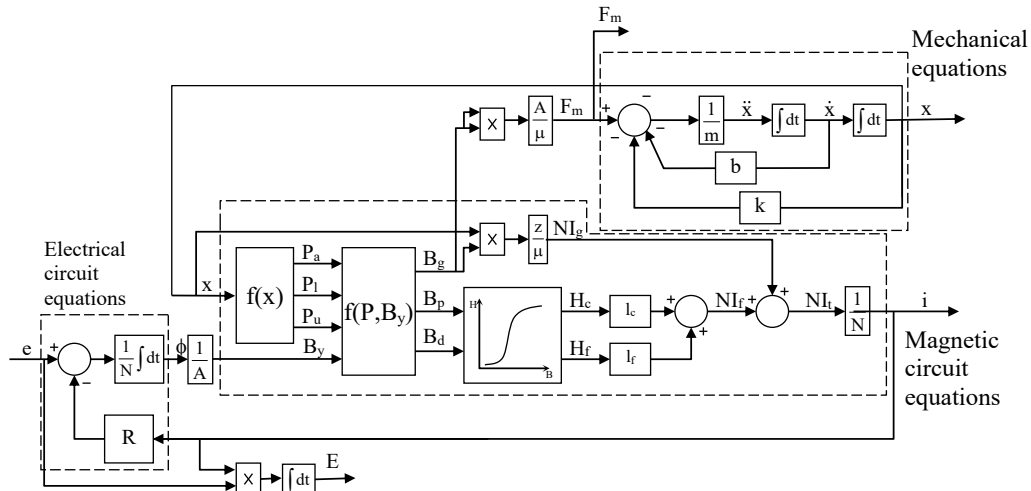


Figure 2: Block diagram of Simulink model [1].

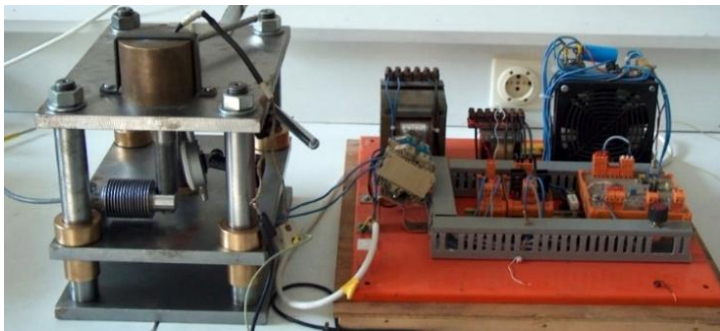


Figure 3: Experimental setup.

Fig. 4 shows the static characteristics of the magnetic circuit for different currents and air gaps with a coil wire diameter of $d = 0.5$ mm. In the tests, the disc was fixed at certain air gaps, and the magnetic force was measured by applying different currents to the coil. Measurements could not be performed because the disc could not be fixed at small air gaps and higher currents, where the magnetic force reached very high values.

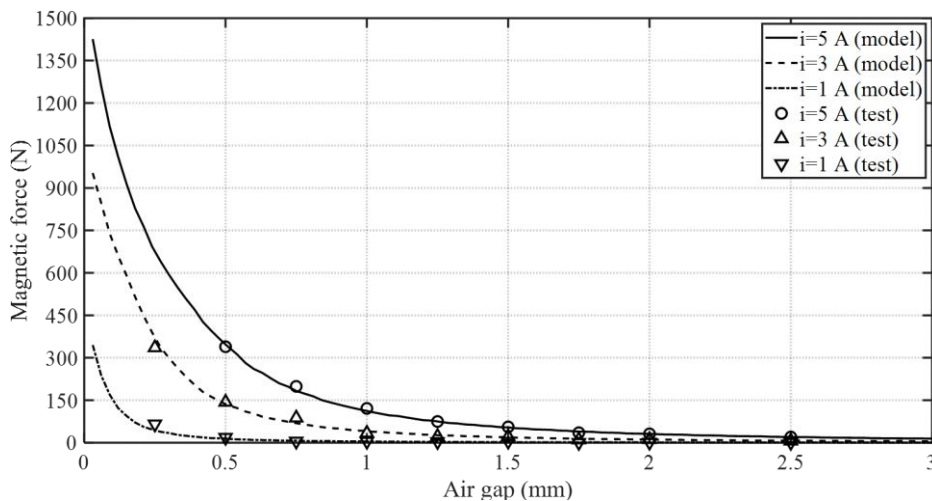


Figure 4: Static characteristics of the magnetic circuit ($d = 0.5$ mm).

The simulation results were also added to Fig. 4, and it was found that they are in good agreement with the experimental results. As seen in the figure, for a given current, the magnetic force is considerably low at large air gaps, increasing significantly as the air gap decreases. Moreover, the magnetic force increases with increasing current for the same air gap. Theoretically, when there is no holding gap ($x_t = 0$, $x_h = x$), the magnetic force approaches infinity, as can be seen from Eq. (6). To prevent the magnetic force from tending to infinity, a protrusion is made on the disc to provide the holding gap (x_t). Thus, when the magnetic energy attracts the disc to the magnet, an air gap remains between the disc and the magnet, and the force is not infinite. Since the holding gap provides an additional air gap to the disc's displacement, a higher magnetic force is required to attract the disc when the magnetic circuit is energized, meaning that the current must reach higher values. This means that the response speed decreases for the same d . However, since the disc is held with a lower magnetic force in the larger holding gap, the disc returns to its initial position in a shorter time.

Fig. 5 shows the experimentally obtained coil currents in the magnetic circuit given in Fig. 1. In the tests, a 12.5 V input voltage was applied to the coil for three different wire diameters. No spring was used in the magnetic circuit, and the magnetic force caused the disc to move upward. The disc thickness was $w = 7.5$ mm, and the air gap was $x_h = 2.1$ mm ($x_t = 0.1$ mm). As seen in Fig. 5, the response speed increases and the coil current reaches higher values as the wire diameter increases. The results obtained using the Simulink model in Fig. 2 have also been added to Fig. 5. The model results are consistent with the test results.

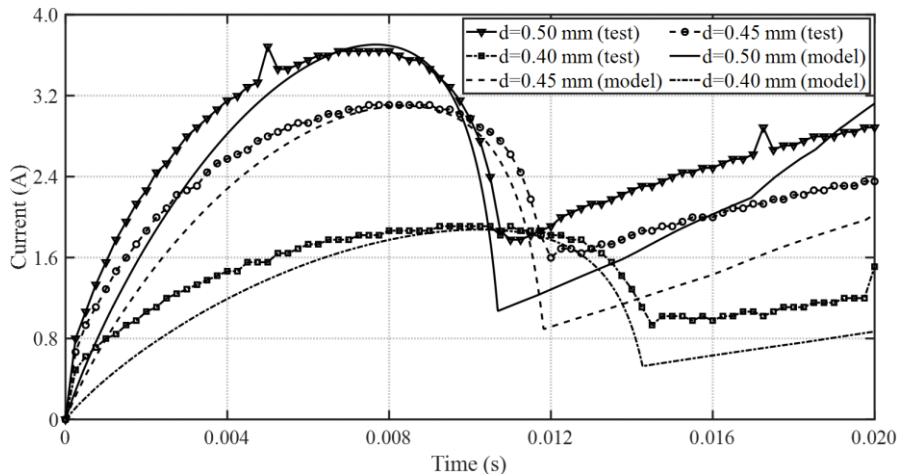


Figure 5: Effect of coil wire diameter.

In the disc type of magnetic circuits, w is generally chosen to be the same as r_5 shown in Fig. 1 [22]. Changing the disc thickness affects the flux line and the amount of moving mass. Fig. 6 shows the experimentally obtained force–displacement characteristics for three disc thicknesses at three currents. Measurements could not be performed at small air gaps because the disc could not be held stably due to the high magnetic force. As seen in Fig. 6, the magnetic force is similar for disc thicknesses of 7.5 mm and 6 mm, while reducing the disc thickness to 4 mm significantly decreases the magnetic force. Therefore, in the disc type of magnetic circuits, the disc thickness should not be reduced beyond a certain ratio ($\sim 80\%$).

To determine the effect of disc thickness on dynamic behaviour, the magnetic circuit was tested without a spring for disc thicknesses of $w = 7.5$ mm and $w = 6$ mm. A voltage of 25 V was applied to the coil, and the disc was pulled upward by the magnetic force from distances of $x = 1, 2, 3,$ and 4 mm. The experimentally obtained current curves are shown in Fig. 7. As seen from this figure, the response speed increases as the disc thickness decreases due to the reduced mass. Additionally, the difference in response times increases as the displacement of the disc increases.

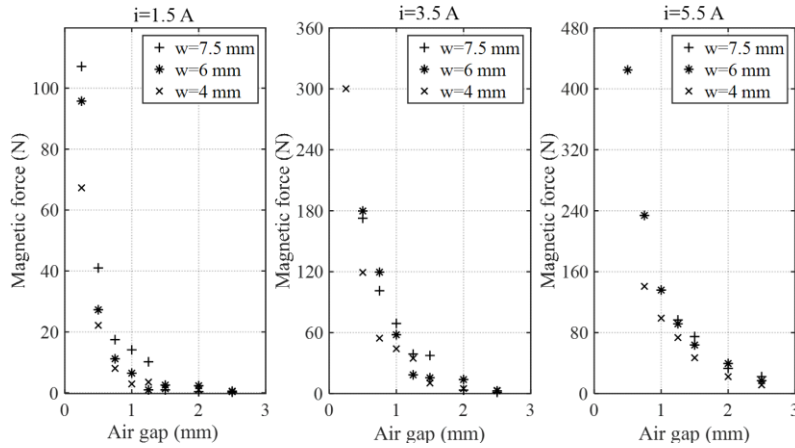


Figure 6: Effect of disc thickness on static characteristics.

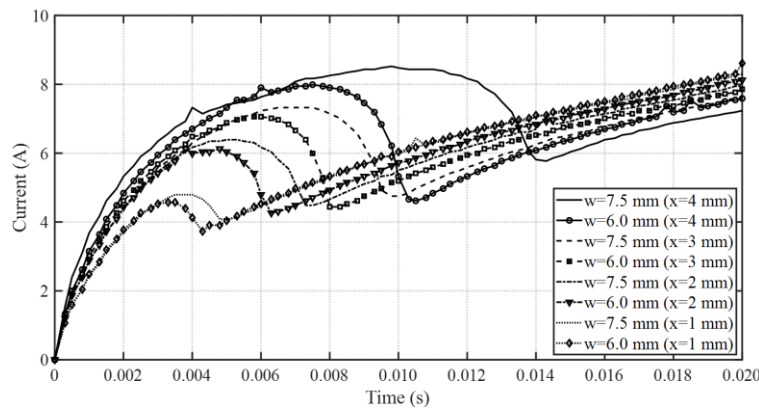


Figure 7: Effect of disc thickness on dynamic characteristics.

2.4 Design of experiment (DoE)

In the disc type of magnetic circuit, when the coil is energized, the magnetic force overcomes the opposing spring force and moves the disc towards itself. When de-energized, the disc returns to its initial position under the spring force. Therefore, the dynamic behaviour of the magnetic circuit must be considered for both opening and closing conditions. In this study, the parameters affecting the opening and closing behaviour of the magnetic circuit, including the holding gap (x_t), disc thickness (w), and coil wire diameter (d), were examined, and the levels for each parameter were determined as given in Table I by considering the fixed pole parameters. Based on these parameters and levels, the design of experiment (DoE) was created according to the Taguchi L18 orthogonal array (Table II).

Table I: Design parameters and their levels.

Parameter	Level 1	Level 2	Level 3
Holding gap, x_t (mm)	0.1	0.15	
Disc thickness, w (mm)	7.5	6	4
Wire diameter, d (mm)	0.4	0.45	0.5

In this study, analyses were carried out assuming a spring with a stiffness of 50 N/mm was used in the magnetic circuit. For the case where a spring is included in the magnetic circuit, the Simulink model shown in Fig. 2 was used, and the switching characteristics of the magnetic circuit obtained with this model are as shown in Fig. 8. To evaluate the effects of the parameters, the same input voltage was applied to the magnetic circuit in all combinations of the DoE. A voltage of 24 V was applied during the first 10 ms , then reduced to 4 V , and set to zero at the

end of 20 ms. Setting the voltage to zero corresponds to giving a close command to the magnetic circuit.

The Simulink model was run for all configurations defined in the DoE, and the switching characteristics, given in Fig. 8, were obtained for each combination. From these curves, the opening time (t_o), the energy consumption during the opening period (E_o), and closing time (t_c) of the magnetic circuit were determined using the model. These values are given in Table II. The closing time and also energy consumption in the closing period can be shortened by using alternative driving techniques, such as reducing the holding current to lower levels, applying a reverse current, etc. Therefore, in this study, only the energy consumption during the opening process was taken into account. Although E_o values in Table II appear to be quite low, they become significant when the magnetic circuit operates for long durations. As seen from Table II, the opening time (t_o) is shorter for larger wire diameters and smaller holding gaps, whereas the closing time (t_c) is shorter for smaller wire diameters and larger holding gaps. In this conflicting situation, design parameters must be selected in accordance with the intended purpose of the magnetic circuit.

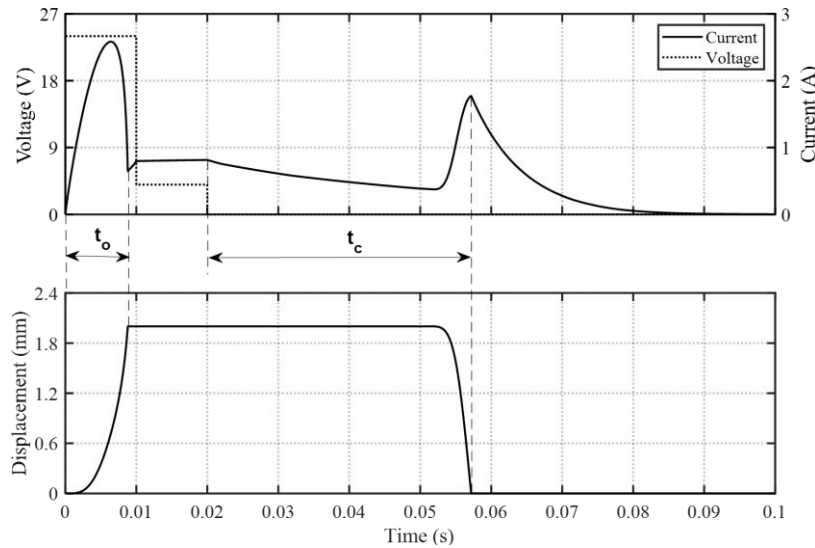


Figure 8: Magnetic circuit switching characteristics.

Table II: Taguchi L18 orthogonal array and model results.

Exp. No	x_t (mm)	w (mm)	d (mm)	t_o (ms)	t_c (ms)	E_o (J)
1	0.1	7.5	0.4	9.25	25.26	0.4236
2	0.1	7.5	0.45	7.11	27.06	0.5288
3	0.1	7.5	0.5	6.11	41.61	0.5525
4	0.1	6	0.4	9.25	24.34	0.4285
5	0.1	6	0.45	7.01	26.42	0.5150
6	0.1	6	0.5	5.99	40.81	0.5326
7	0.1	4	0.4	9.91	19.64	0.4720
8	0.1	4	0.45	7.07	23.65	0.5190
9	0.1	4	0.5	5.90	37.31	0.5150
10	0.15	7.5	0.4	9.47	18.56	0.4455
11	0.15	7.5	0.45	7.24	20.89	0.5515
12	0.15	7.5	0.5	6.18	33.37	0.5735
13	0.15	6	0.4	9.49	17.60	0.4463
14	0.15	6	0.45	7.14	20.28	0.5376
15	0.15	6	0.5	6.07	32.60	0.5535
16	0.15	4	0.4	10.25	13.47	0.4980
17	0.15	4	0.45	7.24	17.82	0.5460
18	0.15	4	0.5	6.00	29.50	0.5380

3. RESULTS AND DISCUSSION

Ideally, both the opening and closing times of magnetic circuits should be as short as possible. However, because the magnetic circuits are powered by an external energy source, minimizing energy consumption is also a critical objective. In this section, analyses were carried out to determine the optimal parameter combination for these targets.

3.1 Signal-to-noise (S/N) analysis

S/N analysis was applied according to the smaller-the-better performance criterion to determine the optimal parameter combination for minimizing the opening time (t_o), the energy consumption (E_o), and closing time (t_c) of the magnetic circuit separately [10, 11, 16, 20, 21]. The S/N analysis results are presented in Table III. The smaller-the-better S/N ratio was calculated as below [11, 20]:

$$S / N = -10 \log \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad (8)$$

where y_i is the real value of the i^{th} experiment, and n is the number of experiments ($n = 18$).

As seen in Table III, the optimal parameter combination for each requirement differs from the others, and the most important parameter in all of them was identified as the wire diameter (d). Table III can be evaluated as follows:

The optimum levels for the t_o are obtained in $x_t = 0.1$ mm, $w = 6$ mm, $d = 0.5$ mm. The order of importance of parameters for the t_o was: $d > w > x_t$. The optimum levels for the t_c are obtained in $x_t = 0.15$ mm, $w = 4$ mm, $d = 0.4$ mm. The optimum levels for the E_o are obtained in $x_t = 0.1$ mm, $w = 6$ mm, $d = 0.4$ mm. The order of importance of parameters for the E_o and t_c was: $d > x_t > w$. As seen in Table III, as the d increases, t_o decreases while the E_o and t_c increase. Additionally, increasing the x_t increases t_o and E_o , but reduces the t_c .

Table III: Mean of S/N ratios.

Level	t_o			t_c			E_o		
	x_t	w	d	x_t	w	d	x_t	w	d
1	-17.35	-17.55	-19.64	-29.14	-26.96	-25.75	6.081	5.780	6.905
2	-17.53	-17.34	-17.07	-26.73	-28.28	-27.02	5.695	6.022	5.468
3		-17.44	-15.62		-28.55	-31.03		5.862	5.290
Delta	0.18	0.21	4.02	2.41	1.59	5.28	0.386	0.243	1.615
Rank	3	2	1	2	3	1	2	3	1

3.2 Variance analysis (ANOVA)

The analysis of variance (ANOVA) was performed to identify the percentage contribution of each parameter to the targets [10, 11, 21]. The ANOVA results are given in Table IV. The R - Sq values of the analyses were found to be above 85 %, confirming the reliability of the obtained results. As seen from Table IV, the ANOVA results revealed that coil wire diameter (d) has the most significant effect on the dynamic performance of the magnetic circuit, with contribution rates of 97.83 % for t_o , 81.03 % for E_o , and 75.82 % for t_c . The effects of the holding gap (x_t) and the disc thickness (w) on the t_o is negligible. x_t was identified as the second highest effective parameter for E_o and t_c , contributing 6.15 % to E_o and 18.42 % to t_c . The effect of w on E_o is 1.42 %, and its effect on t_c is 5.23 %. These results indicate that choosing an appropriate wire diameter and a suitable holding gap leads to an improvement in the dynamic performance of the electromagnet.

3.3 Grey relational analysis (GRA)

In this study, grey relational analysis (GRA) was employed to simultaneously evaluate the opening time (t_o), energy consumption (E_o), and closing time (t_c), and to optimize the parameter combination [20, 21].

Table IV: ANOVA results.

Parameter		x_i	w	d	Error	Total
t_o (R-sq: 98,57 %)	DF	1	2	2	12	17
	Seq SS	0.1217	0.1780	39.9470	0.5844	40.8312
	Contribution	0.30 %	0.44 %	97.83 %	1.43 %	100.00 %
	Adj MS	0.1217	0.089	19.9735	0.0487	
	F-value	2.5	1.83	410.10		
	P-value	0.140	0.203	0.000		
t_c (R-sq: 99.46 %)	DF	1	2	2	12	17
	Seq SS	213.62	60.67	879.48	6.24	1160.02
	Contribution	18.42 %	5.23 %	75.82 %	0.54 %	100.00 %
	Adj MS	213.624	30.335	439.741	0.520	
	F-value	410.74	58.33	845.50		
	P-value	0.000	0.000	0.000		
E_o (R-sq: 88,60 %)	DF	1	2	2	12	17
	Seq SS	0.002287	0.000530	0.030144	0.004241	0.037203
	Contribution	6.15 %	1.42 %	81.03 %	11.40 %	100.00 %
	Adj MS	0.002287	0.000265	0.015072	0.000353	
	F-value	6.47	0.75	42.64		
	P-value	0.026	0.493	0.000		

t_o , t_c , and E_o were evaluated as smaller-the-better, Eq. (9), during the normalization process. In this equation, the indices i and k increase sequentially from 1 to m and n , which correspond to the number of experiments and parameters, respectively. $z_i(k)$ and $y_i(k)$ refer to the normalized and original data, respectively [20].

$$z_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad (9)$$

Here, $\min y_i(k)$ and $\max y_i(k)$ correspond to the minimum and maximum values of $y_i(k)$, respectively. The grey relational coefficient, $\xi_i(k)$, indicating the correlation between the ideal and real result, is calculated as follows [20, 21]:

$$\xi_i(k) = \frac{\Delta_{\min} + \zeta \Delta_{\max}}{\Delta_i(k) + \zeta \Delta_{\max}} \quad (10)$$

$$\Delta_i(k) = |\max z_i(k) - z_i(k)| \quad (11)$$

Here, $\Delta_i(k)$ represents the deviation sequence, and $\max z_i(k)$ indicates the ideal normalized value of $z_i(k)$, corresponding to the best possible normalized result (equal to 1) for the i^{th} experiment. The parameters Δ_{\min} and Δ_{\max} are the smallest and largest values of $\Delta_i(k)$, respectively. The normalization values ($z_i(k)$), distance matrices ($\Delta_i(k)$), and grey relational coefficients ($\xi_i(k)$) were calculated as presented in Table V.

The grey relational grade (GRG) is used to assess the overall impact of multiple responses. For the i^{th} experiment, GRG_i is calculated as the weighted sum of the grey relational coefficients, $\xi_i(k)$, as expressed in [20, 21]:

$$GRG_i = \sum_{k=1}^m \xi_i(k) \quad (12)$$

where m is the number of performance criteria. The largest GRG value is assigned rank 1, followed by the higher ranks in descending order of $GRGs$. A higher GRG indicates a superior process parameter combination.

The grey relational grades (GRG_i) were calculated for two different cases where t_o , t_c , and E_o were all minimum ($m = 3$), and only t_o and E_o were minimum ($m = 2$), and the grade values and their rankings were given in Table VI.

Table V: Normalization values, grey relational coefficients.

Exp. No.	y			z			Δ			ξ		
	t_o (ms)	t_c (ms)	E_o (J)	t_o	t_c	E_o	t_o	E_o	t_o	t_o	t_c	E_o
1	9.25	25.26	0.4236	0.2299	0.5810	1.0000	0.7701	0.4190	0.0000	0.3937	0.5441	1
2	7.11	27.06	0.5288	0.7218	0.5171	0.2982	0.2782	0.4829	0.7018	0.6425	0.5087	0.416
3	6.11	41.61	0.5525	0.9517	0.0000	0.1401	0.0483	1.0000	0.8599	0.9119	0.3333	0.368
4	9.25	24.34	0.4285	0.2299	0.6137	0.9673	0.7701	0.3863	0.0327	0.3937	0.5642	0.939
5	7.01	26.42	0.5150	0.7448	0.5398	0.3903	0.2552	0.4602	0.6097	0.6621	0.5207	0.451
6	5.99	40.81	0.5326	0.9793	0.0284	0.2728	0.0207	0.9716	0.7272	0.9603	0.3398	0.407
7	9.91	19.64	0.4720	0.0782	0.7807	0.6771	0.9218	0.2193	0.3229	0.3517	0.6952	0.608
8	7.07	23.65	0.5190	0.7310	0.6382	0.3636	0.2690	0.3618	0.6364	0.6502	0.5802	0.440
9	5.9	37.31	0.5150	1.0000	0.1528	0.3903	0.0000	0.8472	0.6097	1.0000	0.3711	0.451
10	9.47	18.56	0.4455	0.1793	0.8191	0.8539	0.8207	0.1809	0.1461	0.3786	0.7343	0.774
11	7.24	20.89	0.5515	0.6920	0.7363	0.1468	0.3080	0.2637	0.8532	0.6188	0.6547	0.369
12	6.18	33.37	0.5735	0.9356	0.2928	0.0000	0.0644	0.7072	1.0000	0.8859	0.4142	0.333
13	9.49	17.60	0.4463	0.1747	0.8532	0.8486	0.8253	0.1468	0.1514	0.3773	0.7731	0.768
14	7.14	20.28	0.5376	0.7149	0.7580	0.2395	0.2851	0.2420	0.7605	0.6369	0.6739	0.397
15	6.07	32.60	0.5535	0.9609	0.3202	0.1334	0.0391	0.6798	0.8666	0.9275	0.4238	0.366
16	10.25	13.47	0.4980	0.0000	1.0000	0.5037	1.0000	0.0000	0.4963	0.3333	1.0000	0.502
17	7.24	17.82	0.5460	0.6920	0.8454	0.1835	0.3080	0.1546	0.8165	0.6188	0.7638	0.380
18	6	29.50	0.5380	0.9770	0.4303	0.2368	0.0230	0.5697	0.7632	0.9560	0.4674	0.396

Table VI: Grey relational grades and their rankings.

Exp. No.	GRG for t_o, t_c, and E_o	Rank for t_o, t_c, and E_o	GRG for t_o and E_o	Rank for t_o and E_o
1	0.6459	1	0.6968	2
2	0.5224	18	0.5293	13
3	0.5377	17	0.6398	7
4	0.6322	3	0.6662	5
5	0.5445	16	0.5563	11
6	0.5692	10	0.6839	3
7	0.5515	13	0.4796	17
8	0.5568	12	0.5451	12
9	0.6072	6	0.7253	1
10	0.6289	4	0.5762	9
11	0.5477	14	0.4941	16
12	0.5445	15	0.6096	8
13	0.6393	2	0.5724	10
14	0.5691	11	0.5168	14
15	0.5724	9	0.6467	6
16	0.6117	5	0.4176	18
17	0.5875	8	0.4993	15
18	0.6064	7	0.6759	4

As seen from Table VI, the optimum combination, in which t_o , t_c , and E_o are all minimized, was obtained as Exp. No. 1 ($x_t = 0.1$ mm, $w = 7.5$ mm, $d = 0.4$ mm). The closing time (t_c) can be reduced using alternative techniques, such as applying a reverse current, selecting a lower holding current, etc. Therefore, the GRA was also applied to determine the design that

minimizes t_o and E_o . Based on the *GRG* results for this case, the optimal design was identified as Exp. No. 9 ($x_t = 0.1$ mm, $w = 4$ mm, $d = 0.5$ mm). As a result, although reducing the disc thickness in the disc type of magnetic circuit increases the fringing flux, the response time decreases due to the reduced mass, which reduces the energy consumption during the opening period. Moreover, the holding gap should be kept as small as possible, and the wire diameter should be selected as large.

4. CONCLUSION

In this study, the disc type of magnetic circuit was considered, and the parameters that affect the dynamic behaviour of the electromagnet, designed for an automotive application, were identified. After the effects of these parameters were experimentally demonstrated, studies were conducted on the Simulink model, which was validated with test results. The design of experiment (DoE) was created using the Taguchi L18 orthogonal array approach, based on the selected parameters and their levels. All combinations in the DoE were then implemented in the Simulink model. For each combination, the opening time, the energy consumption during the opening period, and the closing time were obtained. In magnetic circuits, the opening and closing times should be as short as possible, and the energy consumption should be minimized. For this purpose, *S/N* analysis was performed based on the simulation results. Through this analysis, the optimal combination and the order of importance of the parameters were determined for each requirement. The percentage contribution of each parameter was then determined using ANOVA. The analyses performed separately for each response revealed that the optimal parameter combinations differed from one another. Subsequently, the most suitable parameter combination was determined by applying the grey relational analysis (GRA) to evaluate all the requirements simultaneously at an optimal level. GRA was conducted for two different cases. In the first case, all three targets were minimized, while in the second, only the opening time and energy consumption during the opening period were minimized. Because the closing time depends largely on the selected spring and the residual magnetic force in the magnetic circuit. The closing time can be reduced by applying a reverse current, resetting the holding current earlier, and so on. Evaluation of all results revealed that the wire diameter is the most effective parameter affecting the dynamic behaviour of the magnetic circuit. The wire diameter should be as large as possible, and the holding gap should be minimized for a high response speed. The test and analysis results also indicate that reducing the disc thickness up to a certain level (approximately 80 % of its original thickness) increases the response speed of the magnetic circuit. However, further reduction leads to increased leakage flux, which decreases the magnetic force. Therefore, the disc thickness must be optimally selected based on the magnetic circuit characteristics. In the future, the analyses can be performed on magnetic circuits of different structures and sizes, and the results obtained can be generalized.

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