ELECTROMAGNETIC DOOR MECHANISM “POWER-DOOR”

For Adam Johnson - Fisher and Paykel Appliances

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Team 5

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Abstract

This report contains the design process and results of optimising an electromagnet for Fisher and Paykel Appliances, this includes the dimensions of the proposed electromagnet and the improvements in opening and closing forces as well as the reduction in material used. In addition, this report contains details of the electromagnet evaluated at a temperature of 0-40°C and also includes a sensing technique for the electromagnet for door movement and position. The resulting opening forces and closing forces between the permanent magnet and proposed electromagnet are 14.9N and 16.4N, under 20°C and 1400 Ampere-turns in the current coils surrounding the electromagnet. The volume of the proposed electromagnet is 1.5 x $10^{-5}m^3$. The team's proposed design improves the closing and opening forces by 71% and 221% respectively while using 50% less material, the proposed design has a force variation of greater than 90% from 0 to 40°C. The proposed sensing technique for position takes advantage of a difference in time constant of current in the coil when the door is open or closed. This technique measures the current 3 milliseconds seconds after a rising edge of a 15 Hz, 50% PWM duty cycle, and can confirm that the door is open if the current is above 0.8A. This technique is largely unaffected by temperature and becomes more accurate the further the door is opened. The proposed sensing technique for door speed takes advantage of the induced EMF in the current coil due to relative movement in relation to the permanent magnet, this EMF can be measured and is largely unaffected by temperature.

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1 Introduction

The increasing popularity of consumer-friendly appliances has prompted Fisher and Paykel Appliances, an engineering company that specialises in consumer-friendly home electrical appliances, to look into the concept of an electromagnet refrigerator door opener. This electromagnet door opener should provide assisting force in opening and closing the door, as well as provide a braking force for the fridge door if the door is travelling too fast towards the fridge. The client, Adam Johnson from Fisher and Paykel Appliances, has provided an existing electromagnet design and has asked for the design to be optimised and evaluated. Specifically, the client has requested these following criteria to be met:

1. Maximise the opening and closing forces of the electromagnet.
2. Minimise the volume of the ferromagnetic core.
3. Evaluate the performance of the electromagnet at a temperature range of 0-40°C.
4. Propose a technique for the electromagnet to be a sensor, specifically sensing if the door is open or closed, and detecting the speed of door.

The client has also given certain restrictions regarding the design, these include:

1. The coil must fit 900 wires, each wire having cross sectional area of 0.2mm^2.
2. A maximum supply voltage of 24V.
3. The ferromagnetic core must have a thickness of 8mm.
4. The ferromagnetic core and coil must fit in a 100mm by 30mm by 30mm block.
5. The permanent magnet cannot be changed in any way.

The first section of this report will discuss the design process that the team went through to optimise the electromagnet, as well as compare the proposed electromagnet against the client's design to validate the overall improvements in forces and volume, this is done at 1400 ampere-turns for the coil. This will be followed by an evaluation of the proposed design for a temperature range of 0-40°C. Lastly, this report will propose a technique for using the electromagnet as a sensor to detect if the door is closed or opened as well as technique to use the electromagnet to determine the speed of a fridge door. The evaluations were done using FEMM modelling software and appropriate equations which can be found in Appendix C.

2 Existing Electromagnet

The client provided an existing electromagnet to be optimised and evaluated. The client also gave certain restrictions regarding the design, these include:

1. The coil must be large enough to fit 900 wires, each wire having cross sectional area of 0.2mm^2.
2. A maximum supply voltage of 24V.
3. The ferromagnetic core must have a thickness of 8mm.
4. The ferromagnetic core and coil must fit in a 100mm by 30mm by 30mm block.
5. The permanent magnet cannot be changed in any way.

The existing electromagnet is designed with a U-shaped ferromagnetic core with a length of 100mm, thickness of 8mm and a height of 20mm on both ends of the core. The coil is placed in the middle of the ferromagnetic core. It produces an opening force of 4.65N, closing force of 9.60N and a holding force of 2.72N, measured at 1400 Ampere turns, 20 °C and at a 2mm separation distance between the permanent magnet and the ferromagnetic core. It has a block volume of 2.976x10^{-5}m^3 and can be seen in Figure 1.

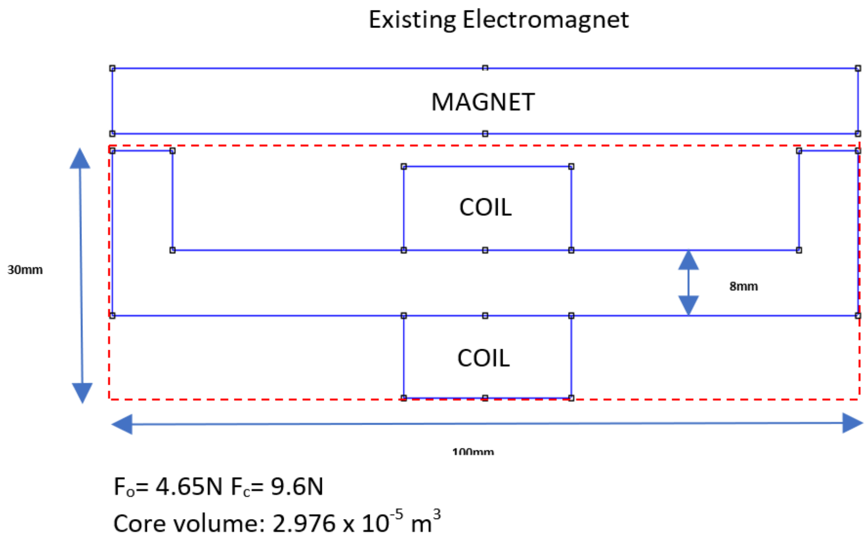


Figure 1. Existing electromagnet

3 Proposed Design

The team's proposed electromagnet design is a variation on the existing design (Figure 2), it is a “U” shaped design with shorter length and width. The coil block is a square 15.5mm by 15.5mm block which can fit more than the clients stated 900 wires, it is placed asymmetrically with one side being in the centre of the design and the other side being on the left side of the design. The proposed design has an opening force of 14.9N and a closing force of 16.3N, measured at 1400 ampere-turns in the coil, 20°C and at a 2mm separation distance between the permanent magnet and the ferromagnetic core.

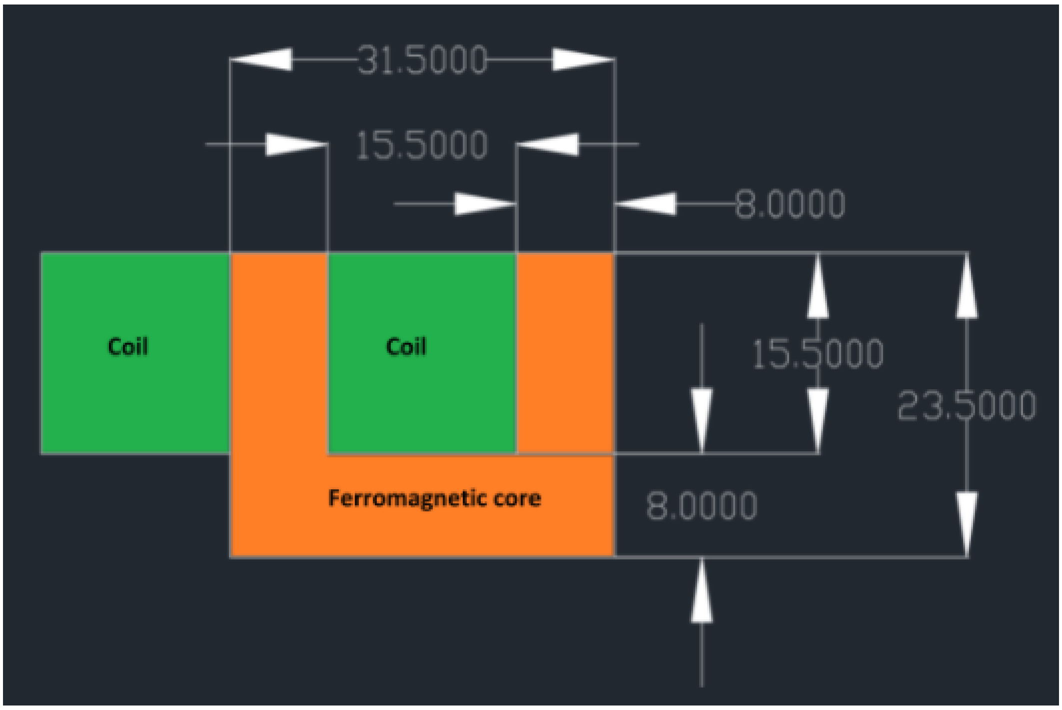


Figure 2. Dimension of Proposed Design, Proposed electromagnet

3.1 Optimising forces

The most important client requirement was to increase the opening and closing forces of the electromagnet. The team started off by looking at existing electromagnet designs and trying out variations on the clients existing design, such as a “E shaped electromagnet” design or by changing the dimensions of the existing design and changing coil placements.

The team found out that in general as the core was decreased in length and width, the opening and closing forces tended to increase, this led to a very compact design which has the shortest length and width possible and still has enough room in the middle for the coil to fit. The team also found that as the coil was moved closer to the permanent magnet, the forces tended to increase, this led to the coil originally being split between left and right hand side of the ferromagnetic core, however it was later found out that placing the coil asymmetrically on the left hand side increased forces. The most important trade-off that the team had to consider was to in regards to the width and height of the coil and its placement, as the client requested that the coil must hold 900 turns of wire, this led to a situation where increasing the width of the coil block would increase the width of the ferromagnetic core, and decrease the height, and vice versa, it was decided in the end to make the coil a square in order to achieve a balance between the width and height.

It was observed that flux lines are not present at the sharp corners of the electromagnet, so the team also experimented with rounding edges to allow flux lines to flow through the ferromagnetic core easily. However, it was found that rounding edges generally decreased the forces, while changing the shape, such as a “E shaped electromagnet” design or making the arms angle inwards did not improve forces by any significant margin, these shapes and their opening and closing forces can be seen in Appendix A. It was decided to stick with the general shape of the clients' design as the shape seemed to have good performance and no other shapes that the team investigated at had better forces.

Overall, our proposed design results in a 221% improvement in opening forces and 71% improvement in closing forces at a 2mm separation distance against the clients existing design, this can be seen in figures 3 and 4. However, after a separation distance of 6mm, the proposed design has a greater opening force (Figure 5) while the client's existing electromagnet has a greater closing force (Figure 6), the team decided to choose our proposed design despite this trade-off as our proposed design offers much higher opening forces and higher closing forces for distances less than 6mm.

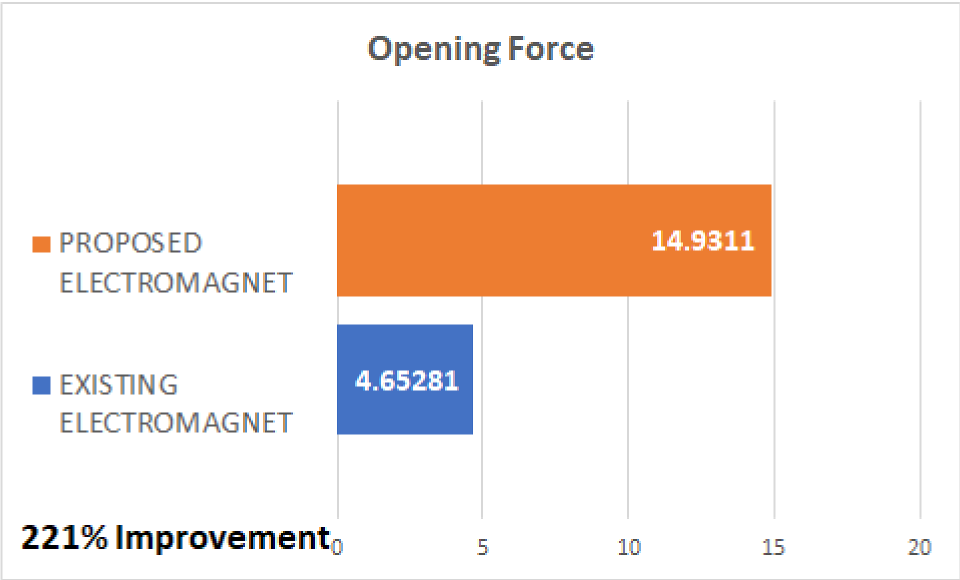


Figure 3. Opening force comparison (N)

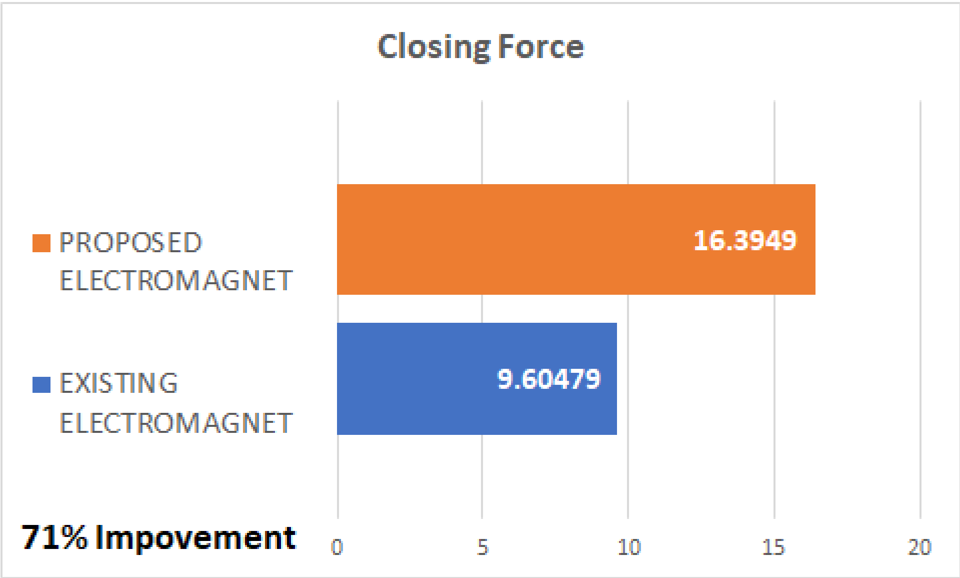


Figure 4. Closing force comparison (N)

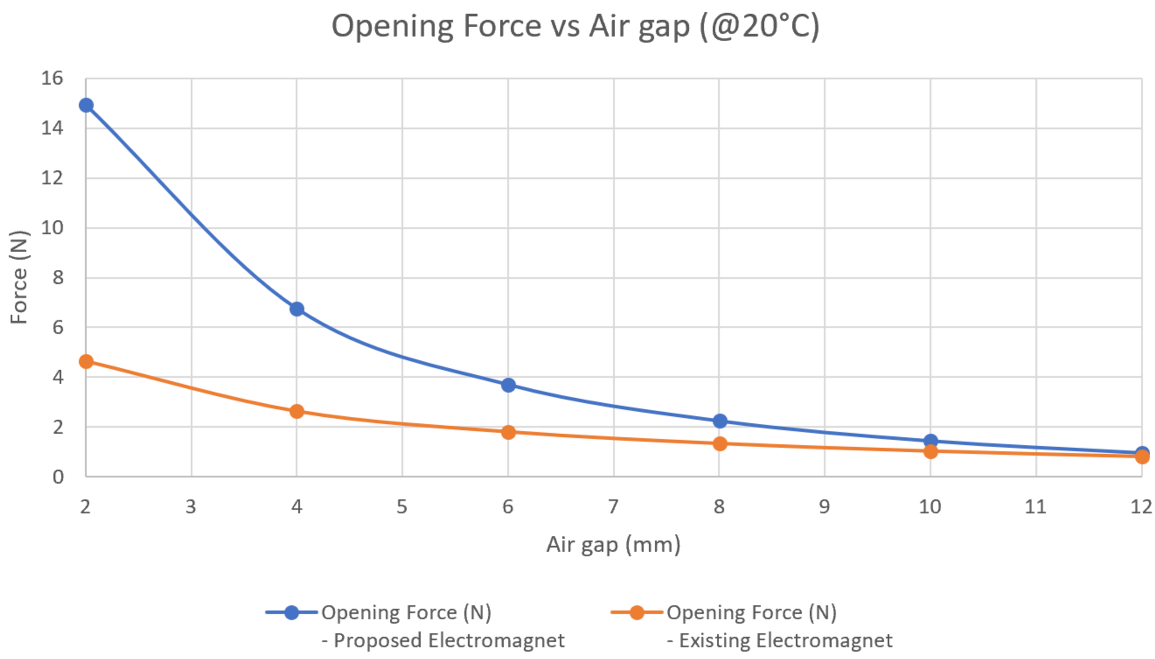


Figure 5. Opening force vs Air gap

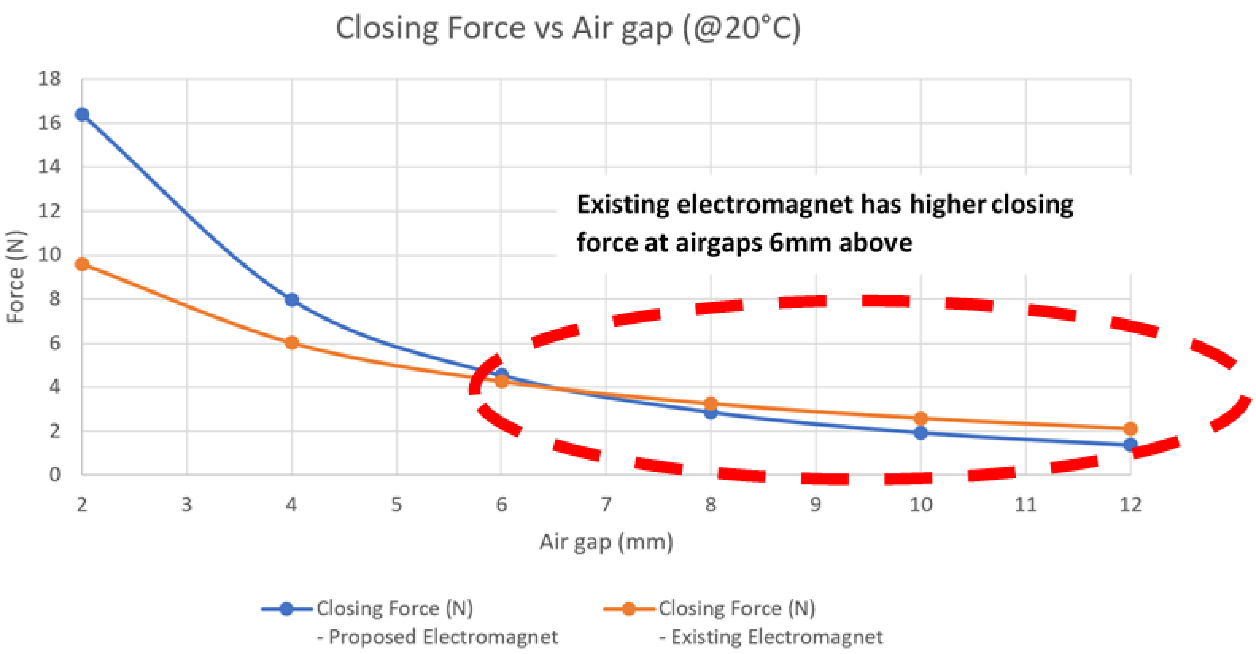


Figure 6. Closing force vs Air gap

3.2 Minimising core volume

Our proposed design leads to a 50% reduced volume compared to the clients' design. The proposed design has a closing force to volume ratio 1.7 times greater than the clients existing design as seen in figure 7 and 8 below, while also having a 6.3 times greater opening force to volume ratio. The client's requirement of minimising the core was easily achieved as our design relies on the ferromagnetic core being as small as possible to maximise the opening and closing forces.

As the team found that adding extra parts to the existing design was not efficient in terms of increasing the forces produced, as well as increase the ferromagnetic core volume. This led to a situation where there was very few trade-offs that the team had to make, as other designs offered greater forces than the clients design at distances of greater than 6mm, however this comes at the expense of less force at a distance smaller than 6mm and will also greater ferromagnetic core volume.

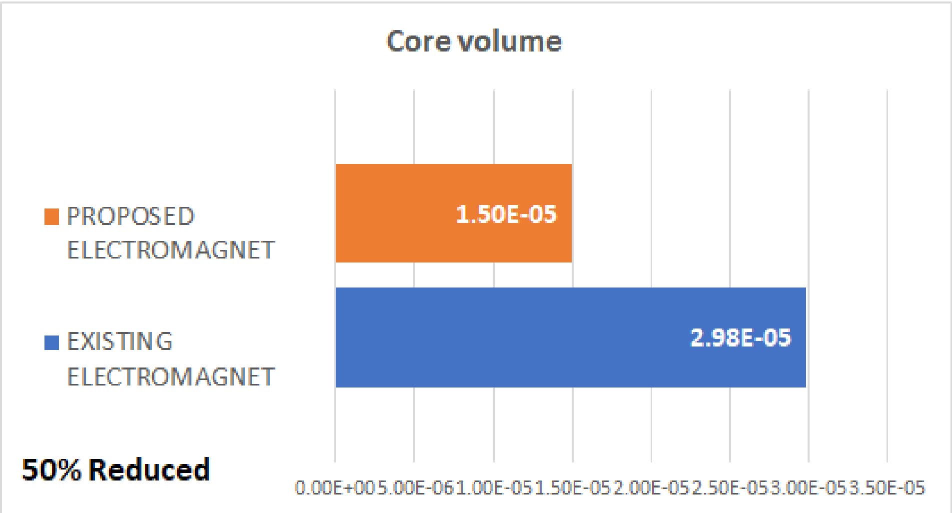


Figure 7. Ferromagnetic core volume comparison (m^3)

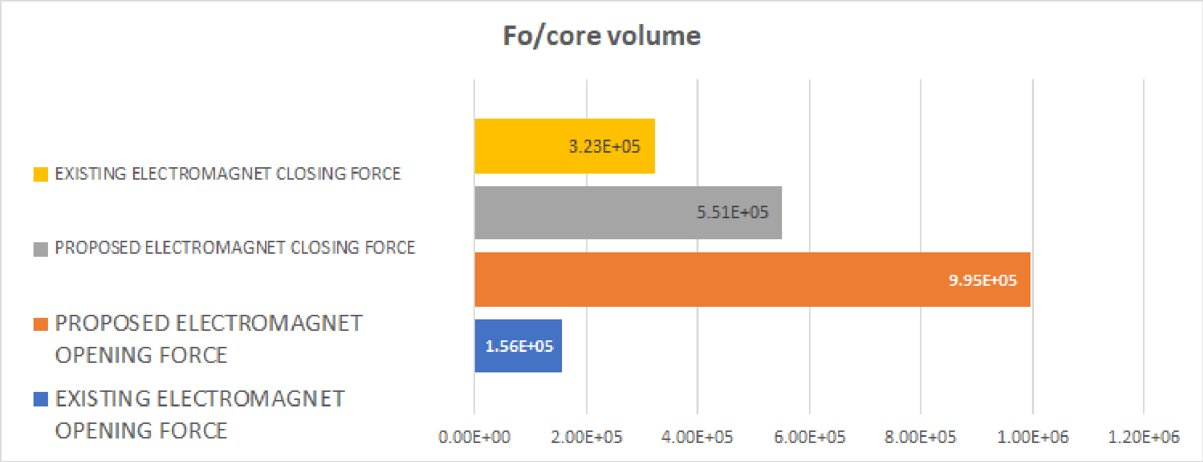


Figure 8. Force (N) per unit volume (m^3) comparison

The figure below (Figure 9) summarises the opening, closing forces and core volume of the existing electromagnet and proposed electromagnet at a separation distance of 2mm.

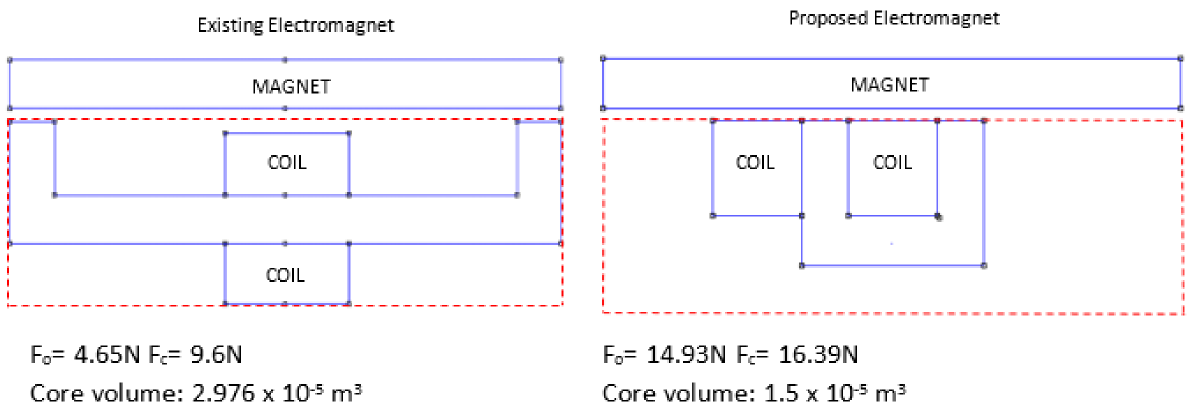


Figure 9. Summary of proposed design against existing design

3.3 Evaluation of temperature effects

The team evaluated the performance of our proposed design against a temperature range of 0-40 °C at 1400 ampere-turns as per the client's request. This was done by changing the BH curve (See Appendix B) of the permanent magnet and the electromagnet as well as the effective resistance of the coil (All About Circuits, n.d.). As a general trend, it was found that as the temperature increased the performance of the electromagnet decreased, this can be seen in Figure 10. By varying the separation distance of the permanent magnet the team found that as the separation distance increases, the forces that the electromagnet produced decrease, this can be seen on the graph below where the air gap is increased by 4mm each time. It can be concluded that after a separation distance of 15mm, there would not be any significant force generated by the electromagnet.

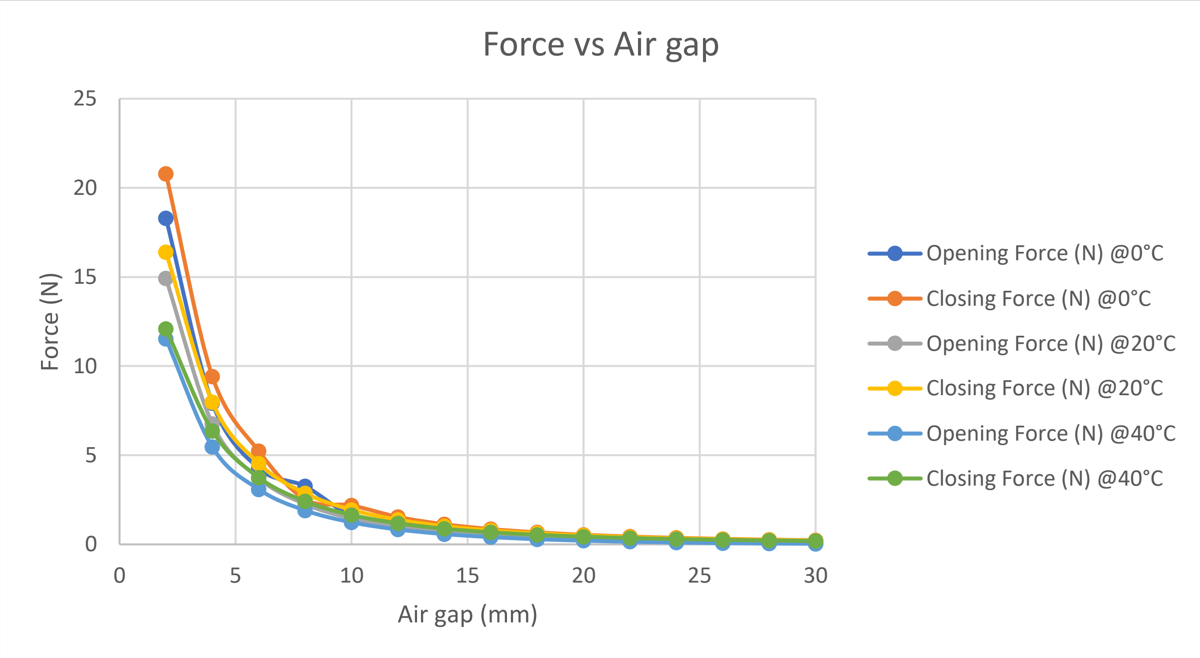


Figure 10. Force against air gap at different temperatures

The team has also evaluated the effects of different duty cycles at 0 and 40°C, the results can be seen in figures 11 and 12. This would give indication on the forces produced when the door is opening or closing due to changing the duty cycle. This was simulated in FEMM by changing the current density of the coil and calculations can be seen in Appendix C. It can be concluded from the results that the forces produced by the coil rises as the duty cycle increases and as the temperature decreases, for comparison sake, the clients request of 1400 Ampere turns corresponds to 42% duty cycle. The results show that the forces generated by the electromagnet are largely affected by the temperature, as between 0 and 40°C the forces can change by almost 100%, this can be seen in Figure 13. The analysis of the duty cycle also includes an evaluation of the time constant as a result of changing temperature and duty cycle, this was done in regards to using the electromagnet as a sensor, it was seen that a rise in temperature resulted in a higher time constant and an increase in duty cycle tended towards a lowered time constant as seen in Figure 14.

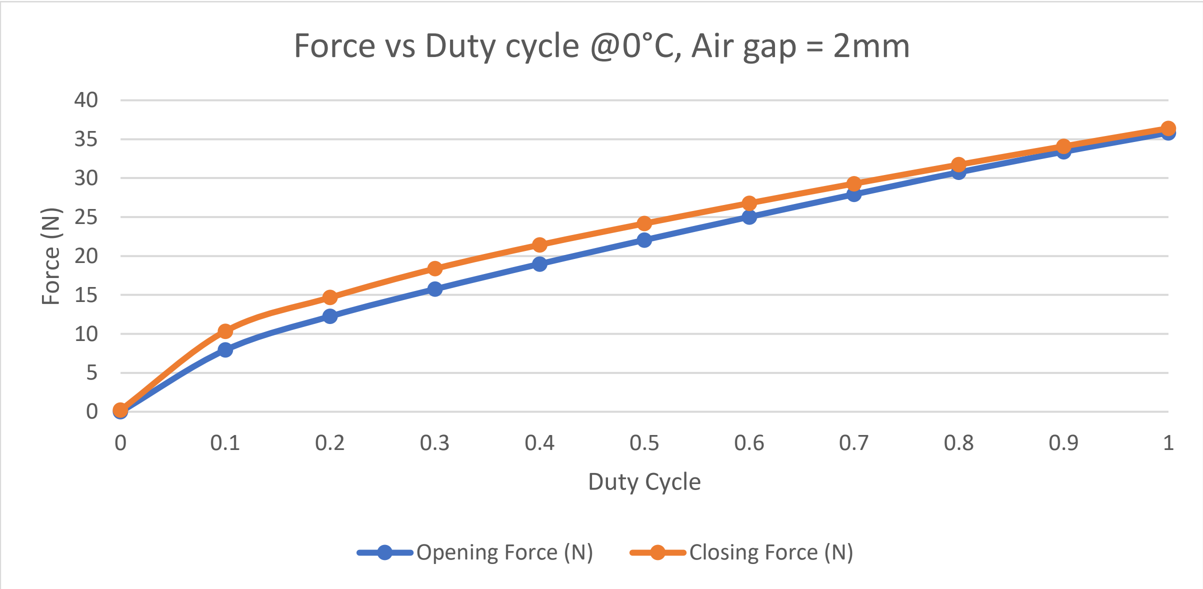


Figure 11. Force vs Duty cycle at 0°C

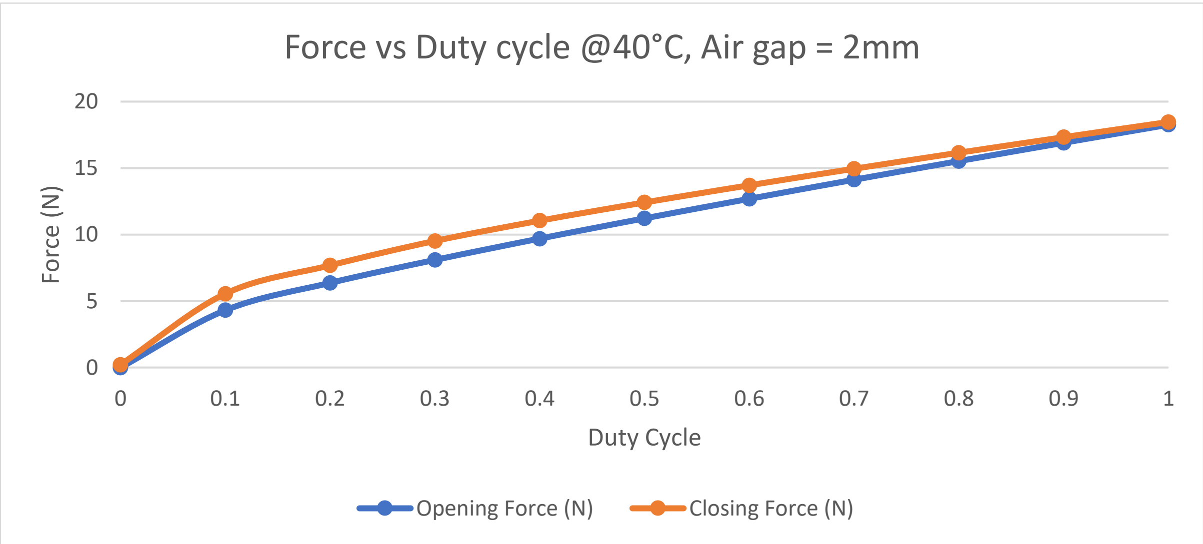


Figure 12. Force vs Duty cycle at 40°C

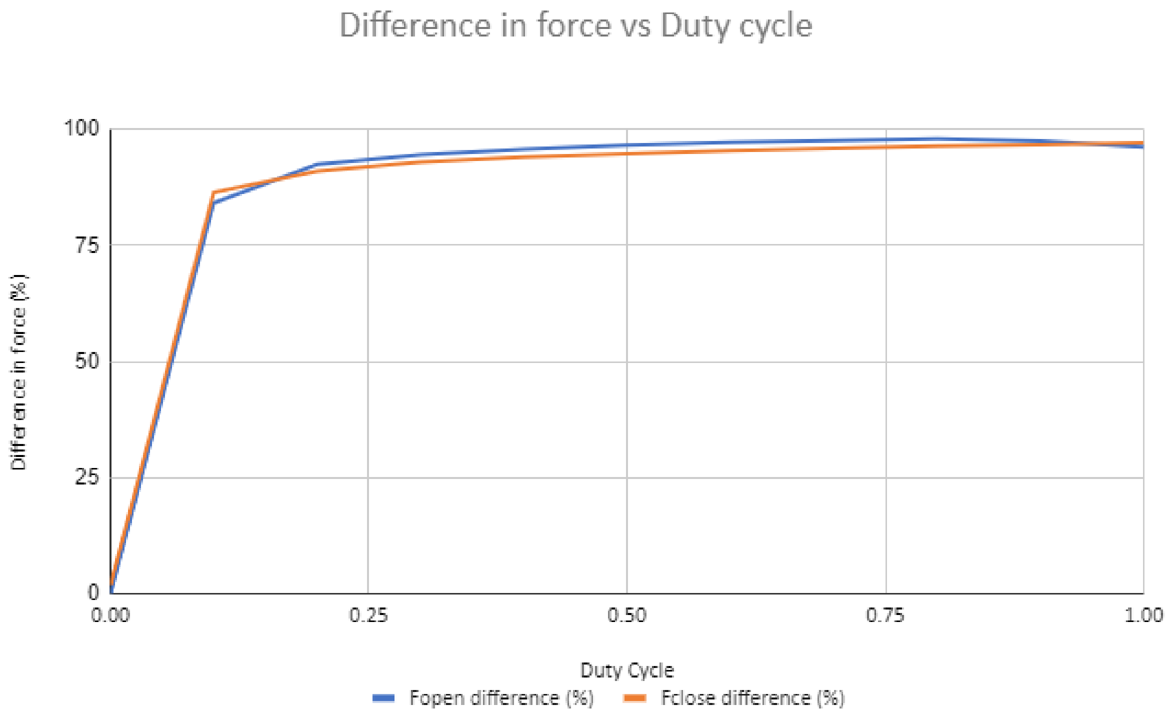


Figure 13. Summary of difference in forces between 0 and 40°C

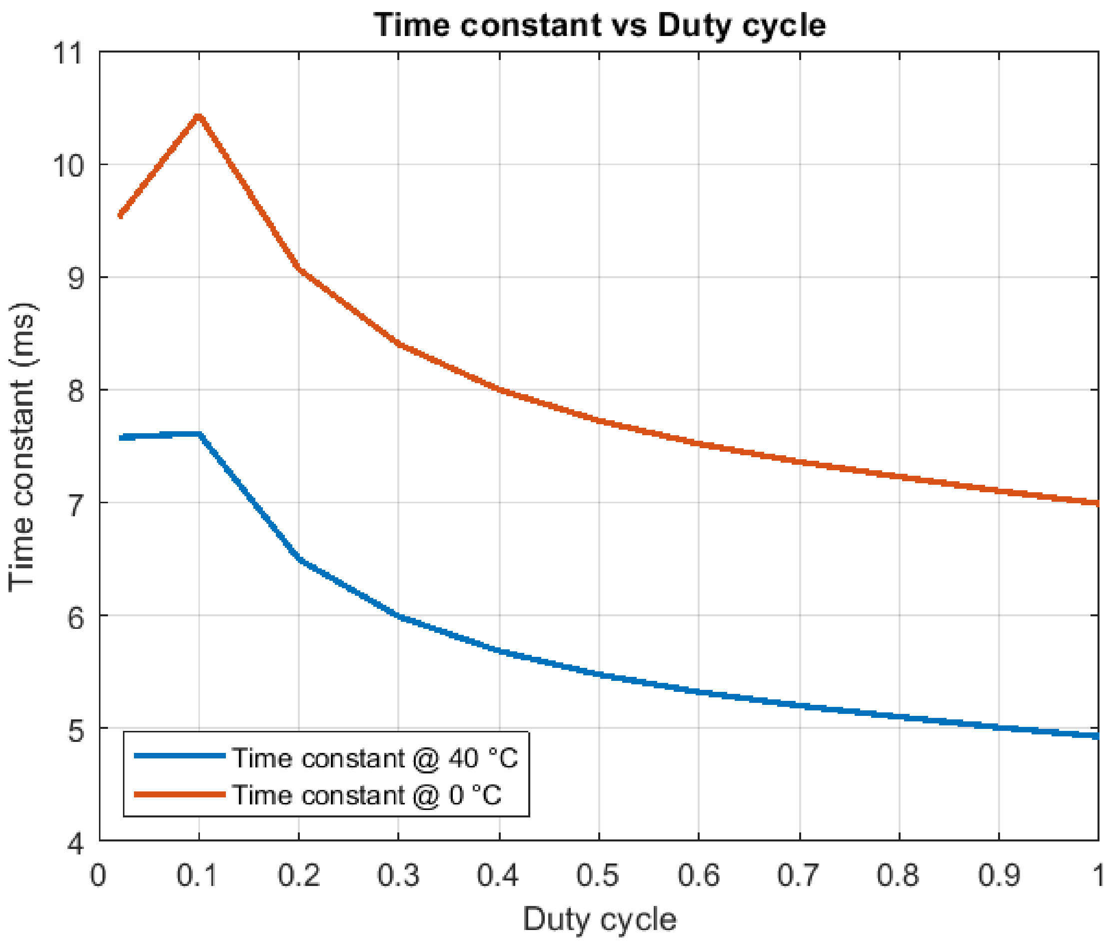


Figure 14. Time constant against Duty Cycle

4 Proposal to use the electromagnet for sensing

4.1 Detecting the position of the door using the electromagnet

The electromagnet can be modelled as an inductor in series with a resistor. In this application, the value of the inductance of the inductor is a function of separation distance from the permanent magnet (*see Figure 15*) and the current in the coil. The inductance and resistance of the coil will also change as a temperature change.

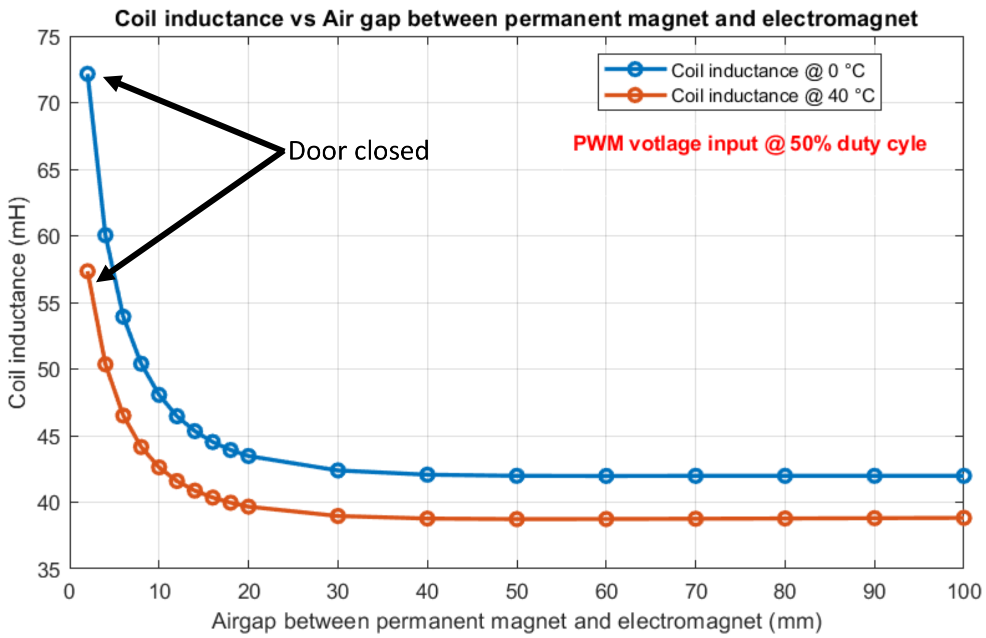


Figure 15. Coil inductance vs Separation distance

A circuit modelling the electromagnet when the door is opened and closed is shown below on Figure 16. Note that the inductance value of the electromagnet is higher when the door is closed. This difference inductance value means that there will be a difference in rise time of the current in the coil. This difference in current can be used to detect if the door is opened or closed. Figure 17 below shows this difference in current rise time when the door is open and closed under two different temperatures, 0°C and 40°C.

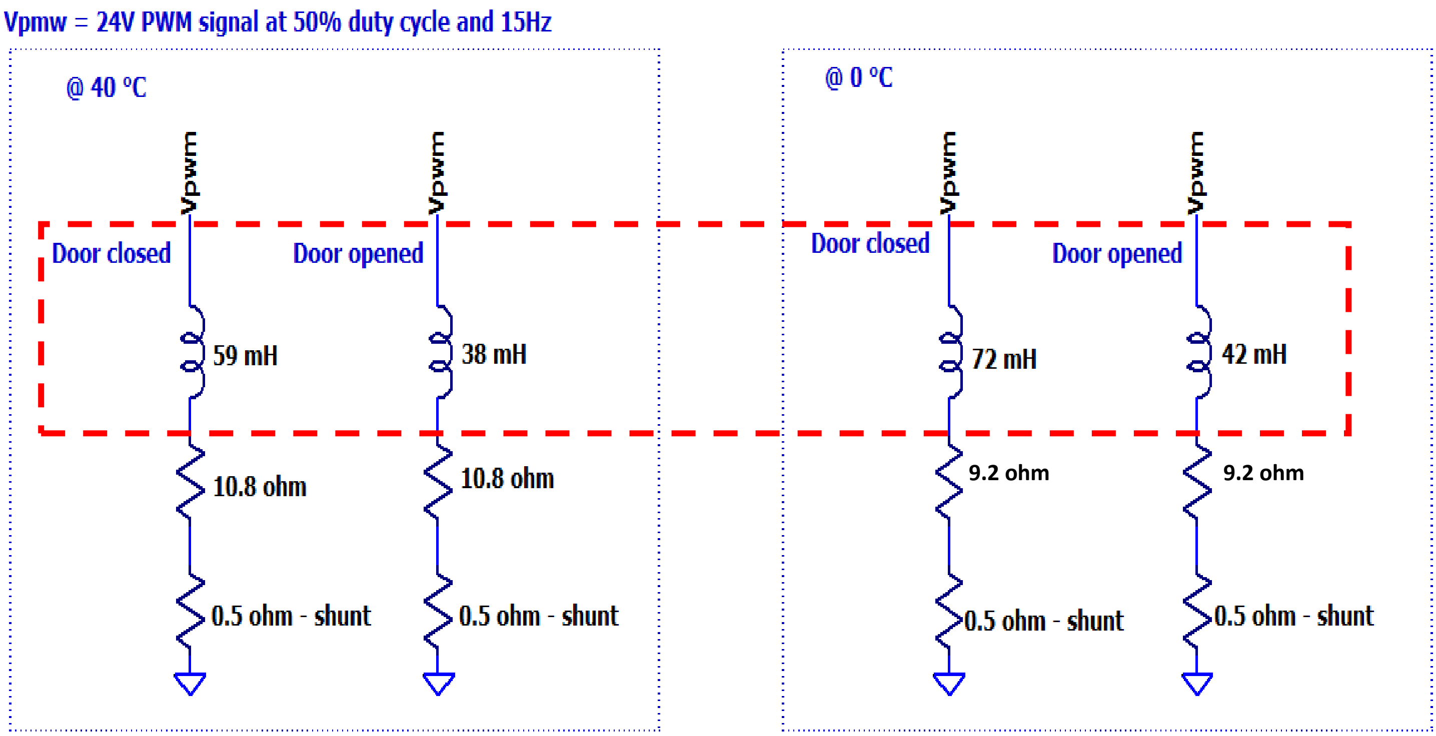


Figure 16. Circuit that models the electromagnet when the door is opened and closed

The inductance values used to model the door being opened are calculated by assuming the door (electromagnet) is infinitely away from the permanent magnet. These inductance values are shown on Figure 16 above for 0°C and 40°C. See Appendix C for the equation used to approximate the inductance values with flux values extracted from FEMM software simulations.

Despite the difference in inductance of the coil when the door is open at 0 and 40 degrees (i.e. current rise time in the coil differs at different temperature), the current in the coil can still be reliably used to detect if the door is opened or not. This is possible because between time t1 and t2 shown on Figure 18 below, the current in the coil are approximately the same regardless if the temperature is 0 or 40 °C.

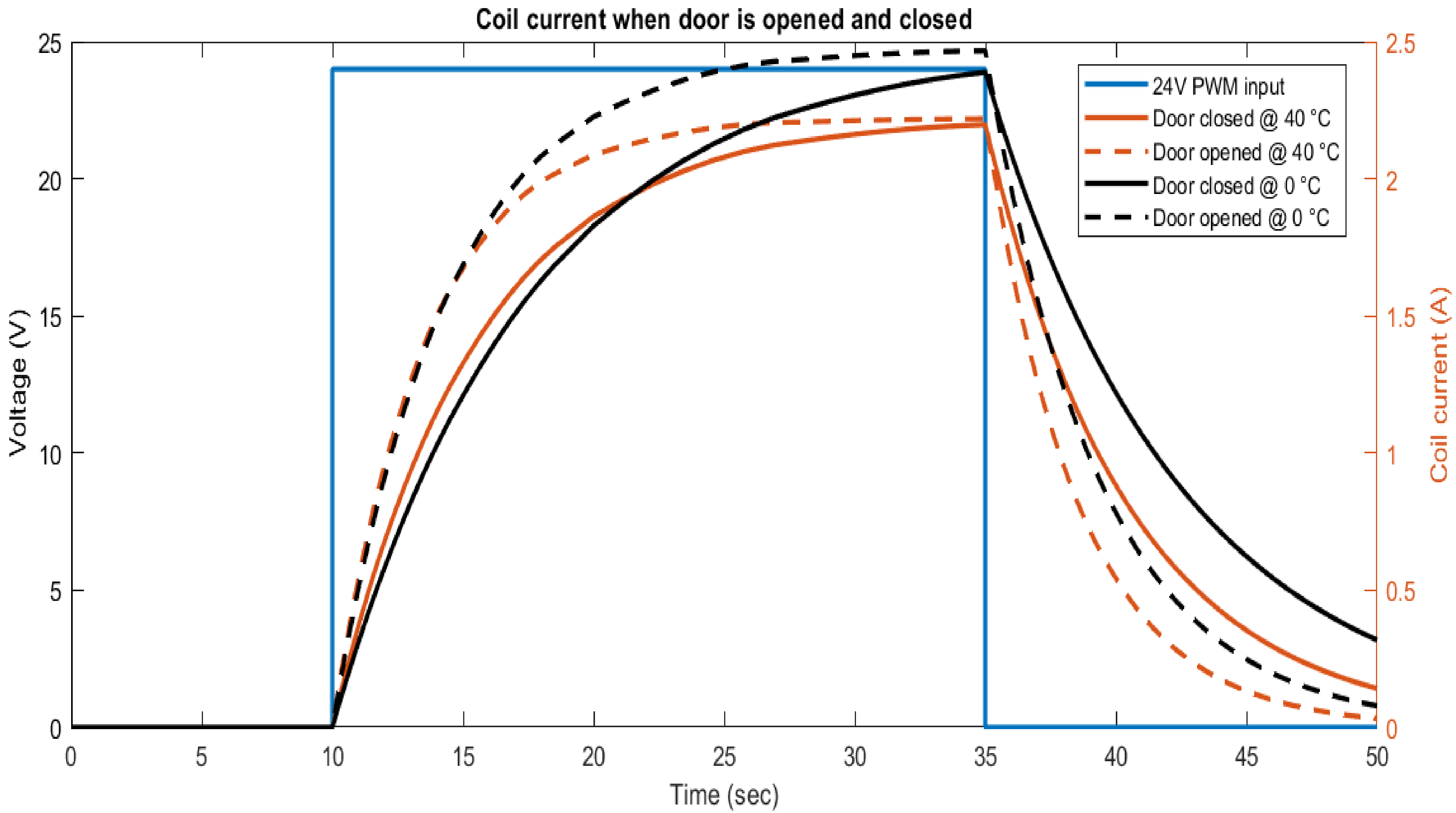


Figure 16. Current rise time in the coil varies when door is open and closed due to coil inductance

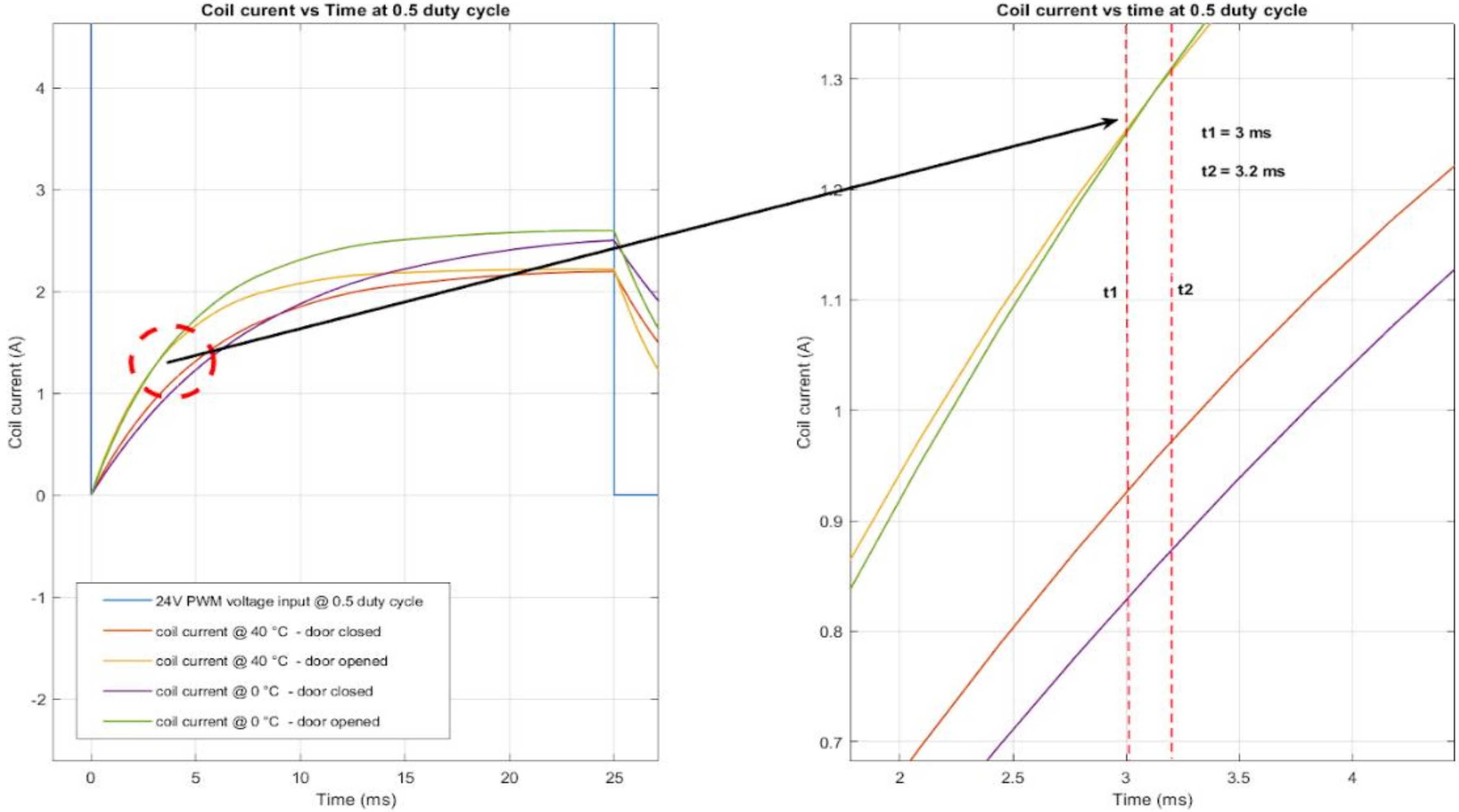


Figure 17. Current measured at 3-3.2 ms is not affected by temperatures at 0 – 40 °C

On Figure 18 above, though the current in the coil when the door is closed has different values between time t1 and t2, this difference in value is insignificant for the sensing technique as the values of the current in the coil when the door is opened are significantly higher.

Shown at Figures 19 and 20 is a high level view of a microcontroller based sensor concept to detect if the door is opened or not by measuring the current of the coil after 3 – 3.2 ms of a rising edge from a PWM signal at 50% duty cycle and at 15 Hz.

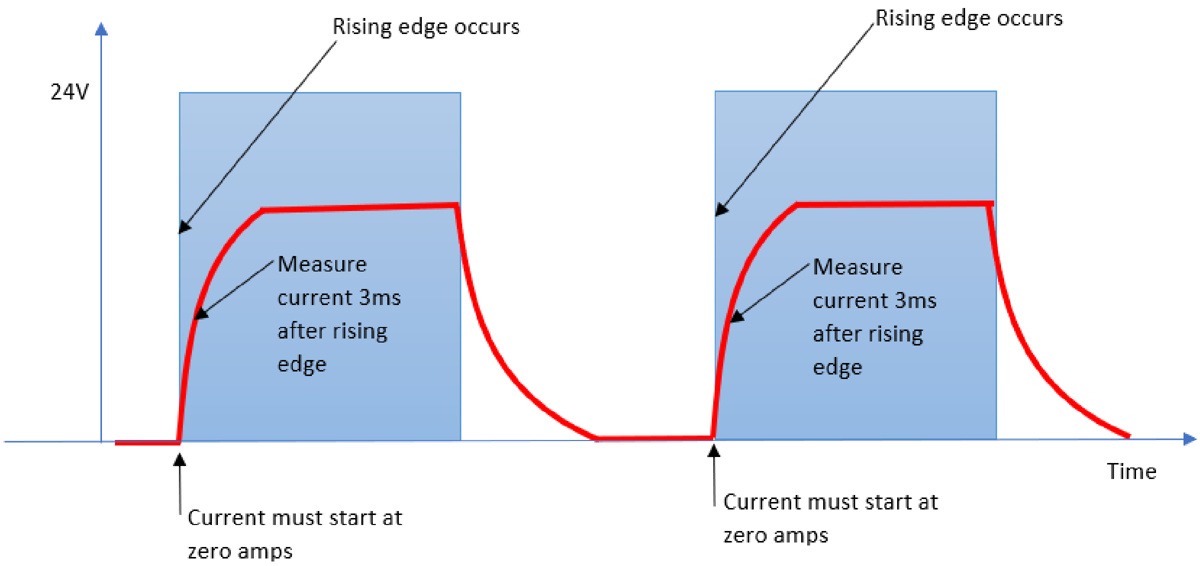


Figure 18. When to measure current

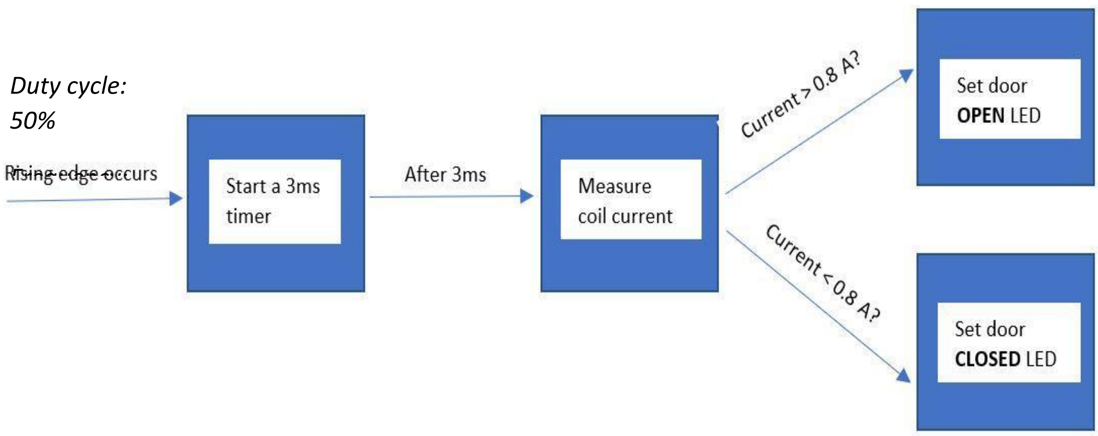


Figure 20. Microcontroller based sensor concept to detect if the door is opened or not by measuring the current of the coil

Shown on Figure 19, the current must be zero at the rising edge of the PWM signal. Otherwise, the current measured at 3ms after the rising edge is not guaranteed to be the same for operations at 0 – 40°C .To ensure the current is zero at the rising edge , a duty cycle between 0.1 to 0.5 must be used and the frequency of the PWM must not be higher than 15 Hz to allow enough time for current to reach zero amps after the "on" time pulse of the PWM.

Note that at Figure 20, the 0.8 A current baseline (i.e. the current value used to determine If the door is opened or not) only works for 50% duty cycle. This current value changes as different duty cycle is used to sense the door position. Use Figure 21 to find the appropriate baseline current. For example, if a 30% duty cycle is used instead, the current needs to be above 0.5 A for the door to be considered open.

Figure 18 above only shows the current in the coil at 50% duty cycle. But the behaviour shown at this Figure 18 (i.e. current is the same at between time t1 – 3ms and t2 – 3.2 ms at 0 and 40 degrees) is extended at different duty cycles too as shown in Figure 21 below. On figure 21, at duty cycles 0.1 – 0.9, the current of the coil when measured at 3ms after a rising edge when the door is opened are very similar at 0°C and 40°C.

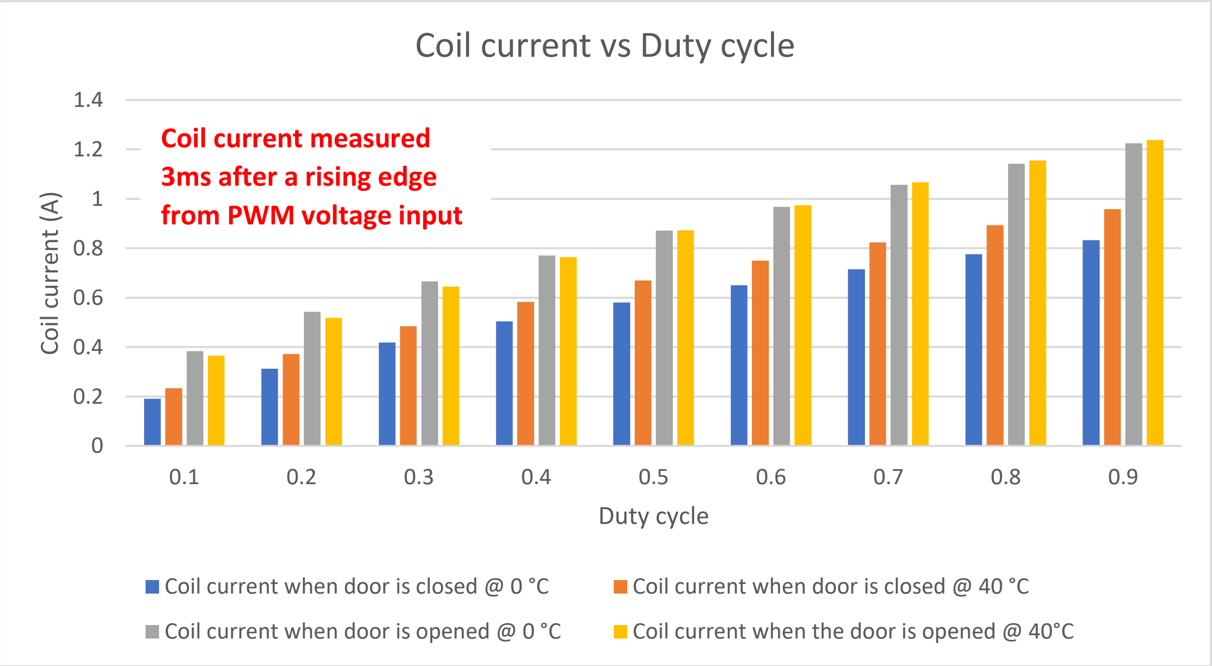


Figure 19. Coil current at 0 and 40 °C are similar for different duty cycles

However, it is recommended that for sensing the door position, the duty cycle must be kept at *0.1 <= Duty cycle <= 0.5*. This is to save power consumption as there is no need to provide high current for the electromagnet to act as a sensor.

Furthermore, at higher duty cycles, the current in the coil does not have time to reach zero amps at steady state during the low side of the duty cycle (See Figure 22). If the current does not reach at zero amps before a rising edge occurs from the PWM signal, it is not guaranteed that the current in the coil will be the same at different temperatures when measured at 3ms after rising edge from the PWM signal due to different time constant. This means there will be some error in current measurement. Figure 22 shows that at 90% duty cycle, the current at point “Ia” is less than the current at point “Ib” even though they are both measured 3ms after a rising edge occurs. Because current at Ib is higher, it could be falsely interpreted as door opened even though the door is not opened.

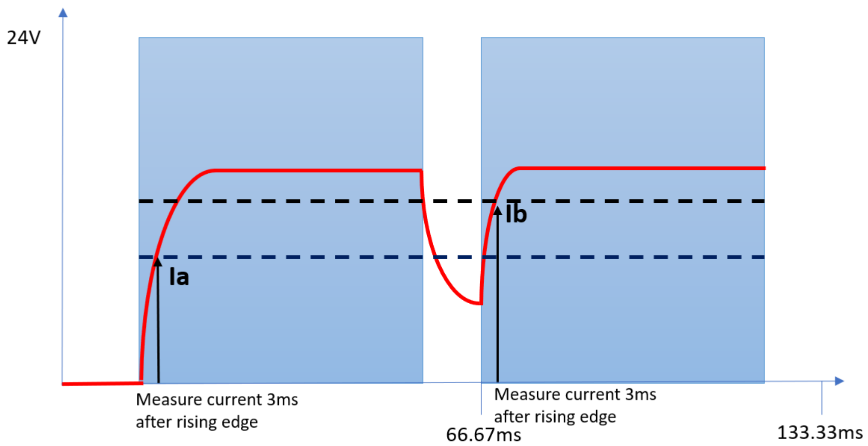


Figure 20. Issues with high duty cycles

The sensing technique presented above only works if the electromagnet is significantly far from the permanent magnet. This means that if the door is only slightly open (e.g. 0.5 air gap), it will be indicated as still closed by the sensor. But Figure 23 below shows that when air gap is around 40mm, the door is guaranteed to be considered opened by the sensing technique. This is because at air gaps 40 mm and above, the inductance of the coil tends to the inductance when the electromagnet is infinitely away from the permanent magnet which is 42 and 38 mH for temperatures at 0 and 40 °C respectively.

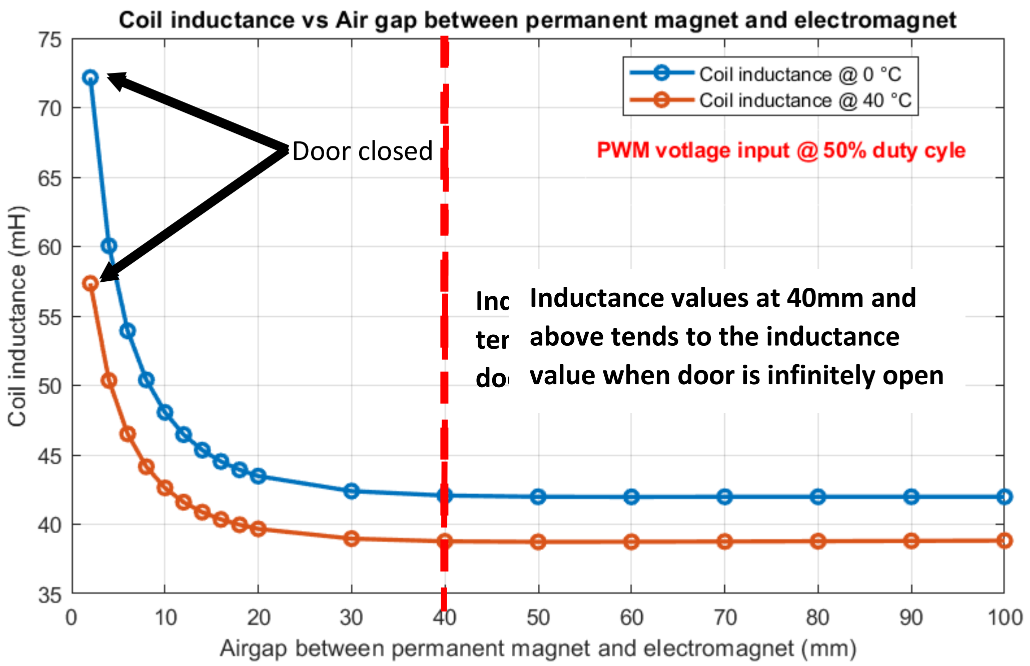


Figure 23. Inductance values at air gaps 40mm and above approaches the inductance when the door is infinitely open

Note that the current sensing technique proposed above measures current that is used to generate the opening force. The current directions are shown on Figure 24 below.

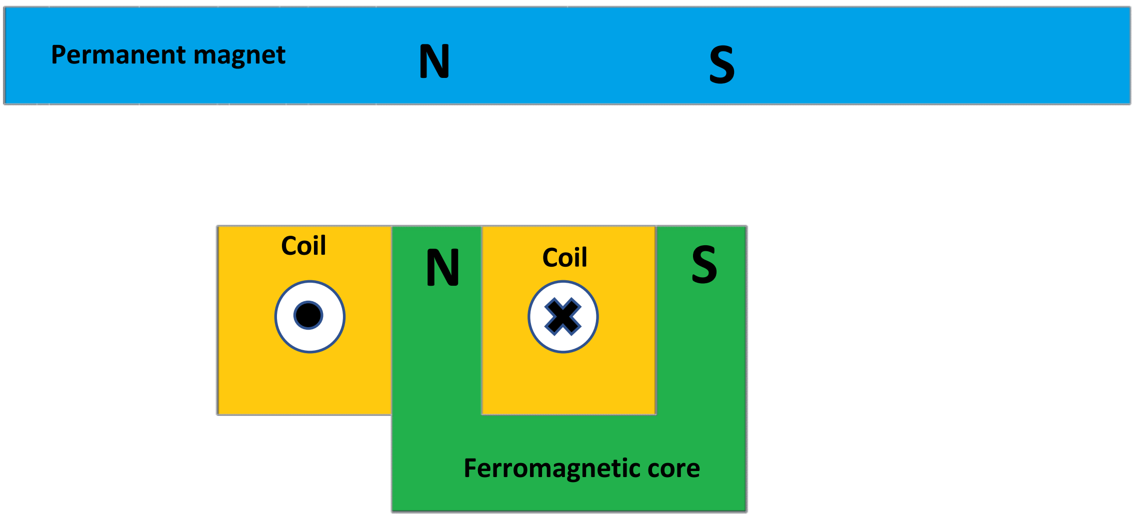


Figure 24. Coil configuration and magnet polarity when using the electromagnet as a sensor

4.2 Detecting the speed of the door using the electromagnet

If the current in the coil is set to zero, it was assumed that only the permanent magnet contributes to the magnetic flux around the electromagnet. This means that the flux is constant at different separation distances between the electromagnet and the coil (see Figure 25 below).

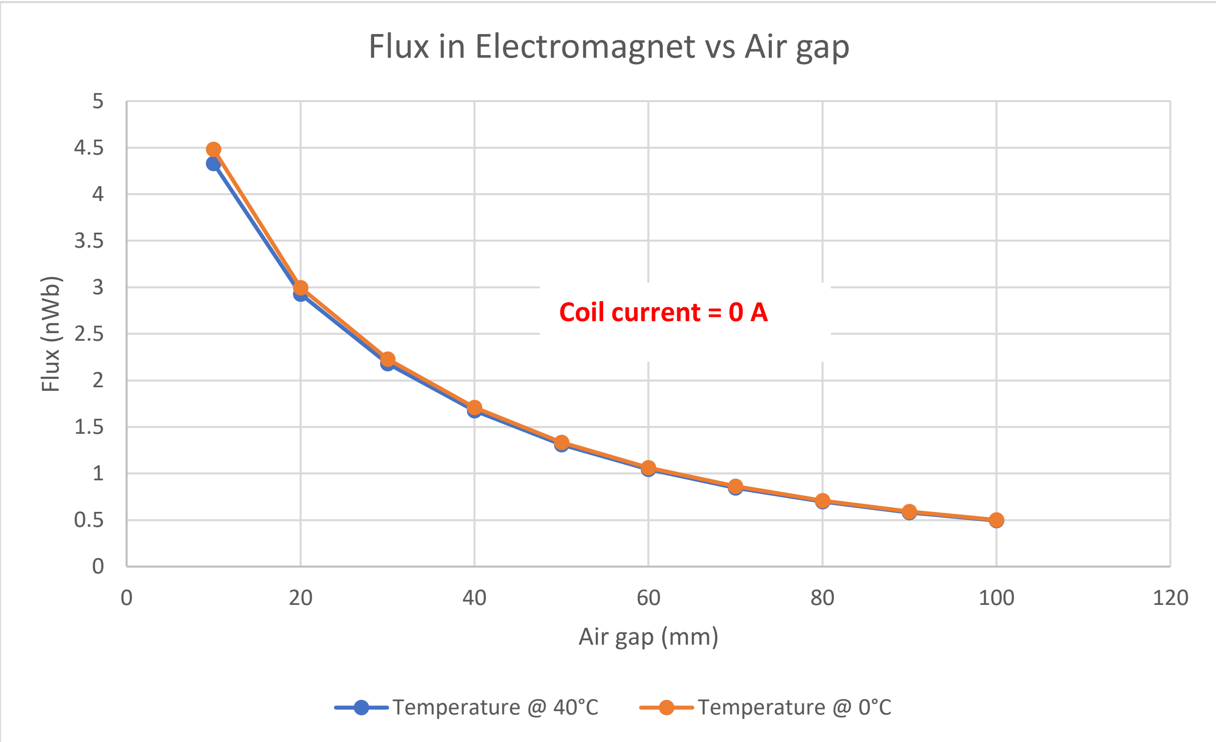


Figure 25. Flux in Electromagnet vs Air gap

If the coil moves through this flux, a voltage in the coil will be induced that is proportional to the speed at which the coil moves. This induced emf can therefore be used to determine how fast the door is approaching the permanent magnet.

The plot at Figure 26 below is generated using the equation below.

$$Emf = N \times \frac{change\ in\ flux}{time}$$

Where N is 900 turns and the change in flux is calculated when the door is 50mm from the permanent magnet and 20mm away from the magnet (see Figure 25 above for flux values).

Figure 26 below shows that this door speed sensing technique can be used at operations at temperatures between 0 – 40°C as the emf values are not significantly altered due to these temperature changes.

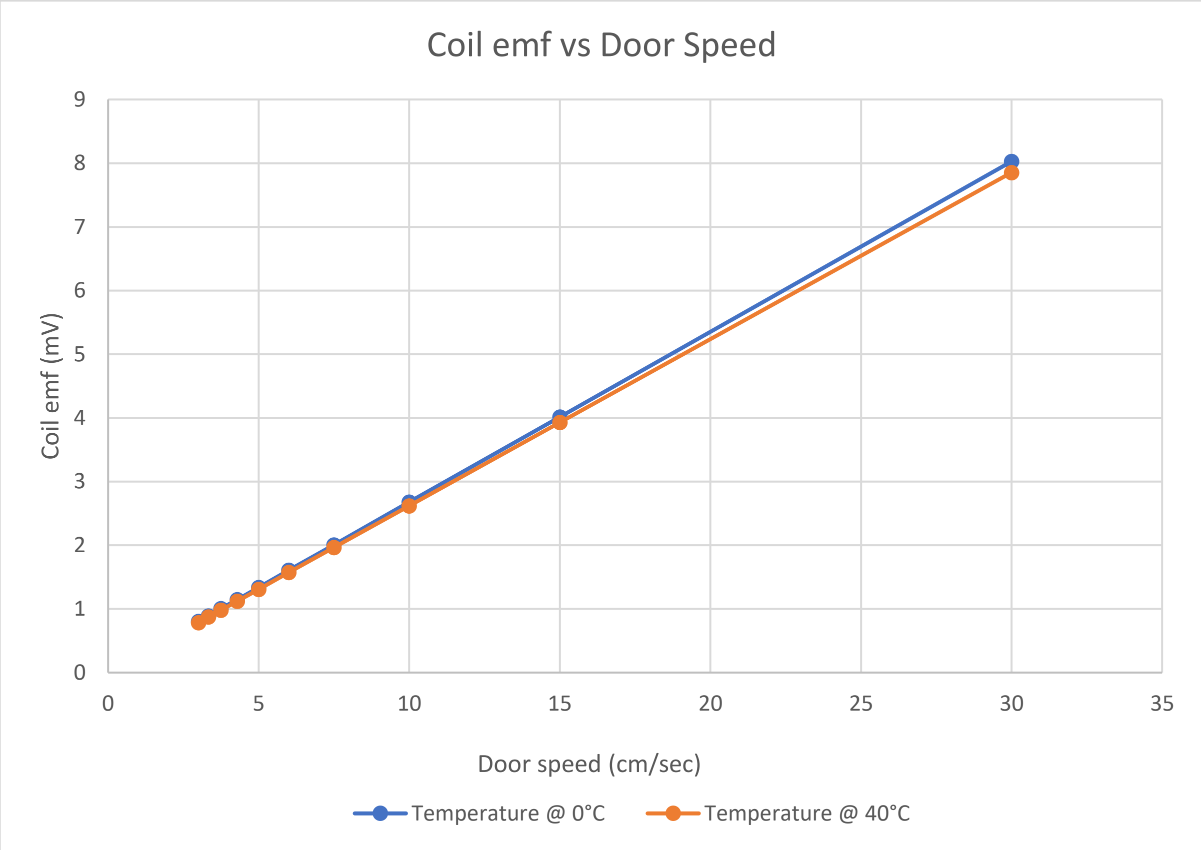


Figure 26. Coil emf vs Door Speed

5 Conclusions

The client, Adam Johnson from Fisher and Paykel Appliances, has requested optimising an existing electromagnet and evaluating it at a temperature range of 0-40°C, while requesting the team to propose a technique that could use the electromagnet as a sensor. The optimisation of the electromagnet was achieved by introducing a shape that increased opening forces by 221% and closing forces by 71%, while using 50% less ferromagnetic material. The temperature performance was evaluated between 0-40°C and a general trend of decreasing forces was observed due to higher temperatures or increased distance between the permanent magnet and ferromagnetic core. It was found that the difference between forces generated at 0°C versus forces generated at 40°C can be greater than 90% during most duty cycles.

The electromagnet can be used as a sensor, as the coil of the electromagnet have different inductance values depending on whether the door is opened or closed. The door is confirmed to be opened if the opening current measured at 3-3.2ms after the rise of a 15Hz PWM signal at 50% duty cycle is above 0.8A, at any temperature range between 0 to 40°C. It is recommended to keep the duty cycle between 10-50% to sense the door's status by sensing whether the current value at 3-3.2ms after the rise of the PWM signal is at a specific baseline current value. Similarly, the electromagnet can be used as a speed sensor due to the EMF induced by relative movement in relation to the permanent magnet, this EMF induced increases as the speed of the door increases and is largely unaffected by temperature.

References

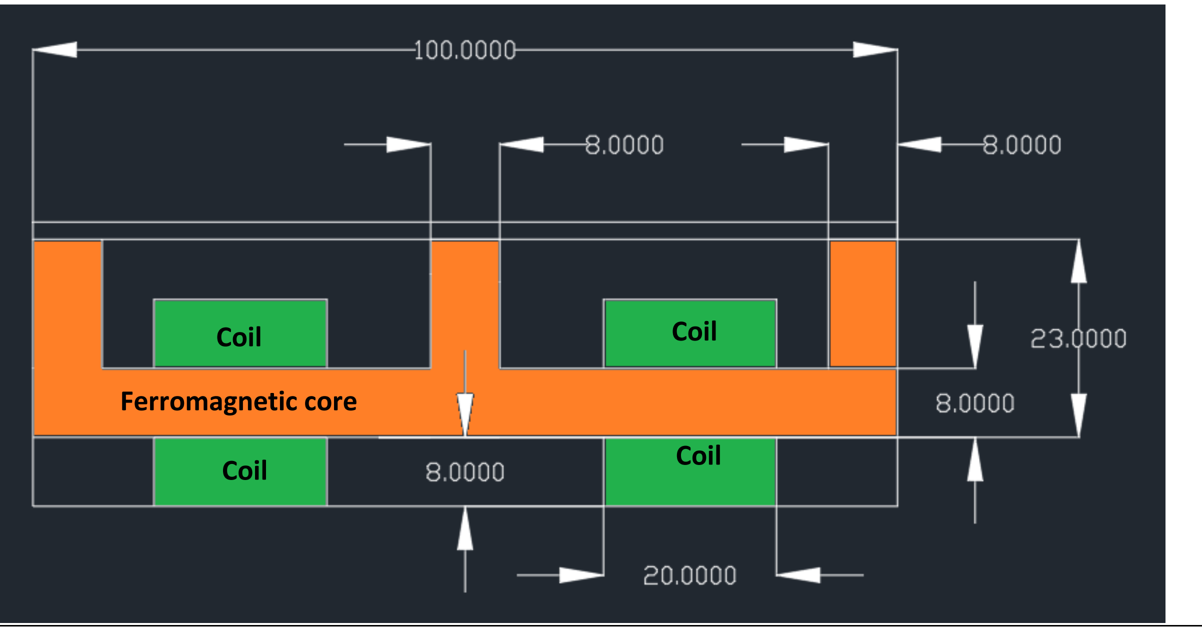
All About Circuits. (n.d.). Retrieved from Temperature Coefficient of Resistance: https://www.allaboutcircuits.com/textbook/direct-current/chpt-12/temperature-coefficient-resistance/

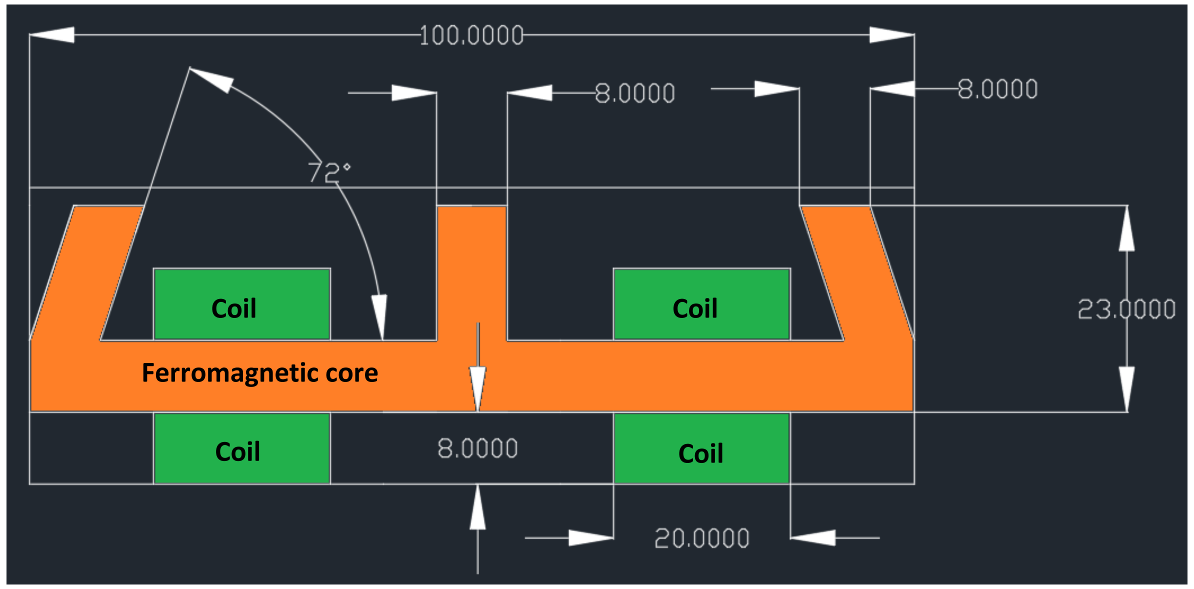
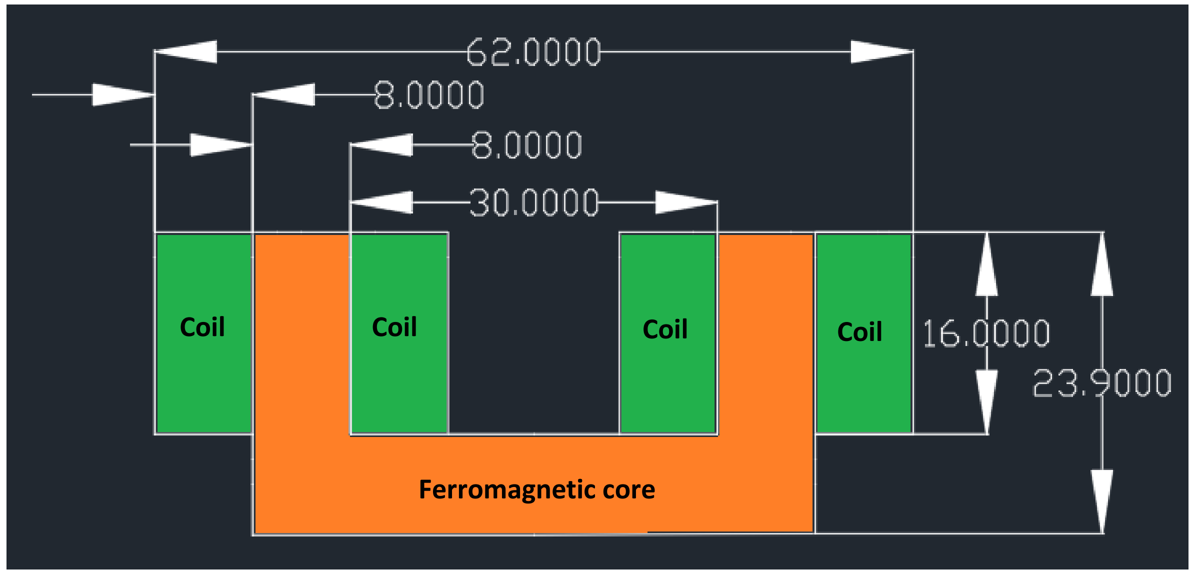
Appendices

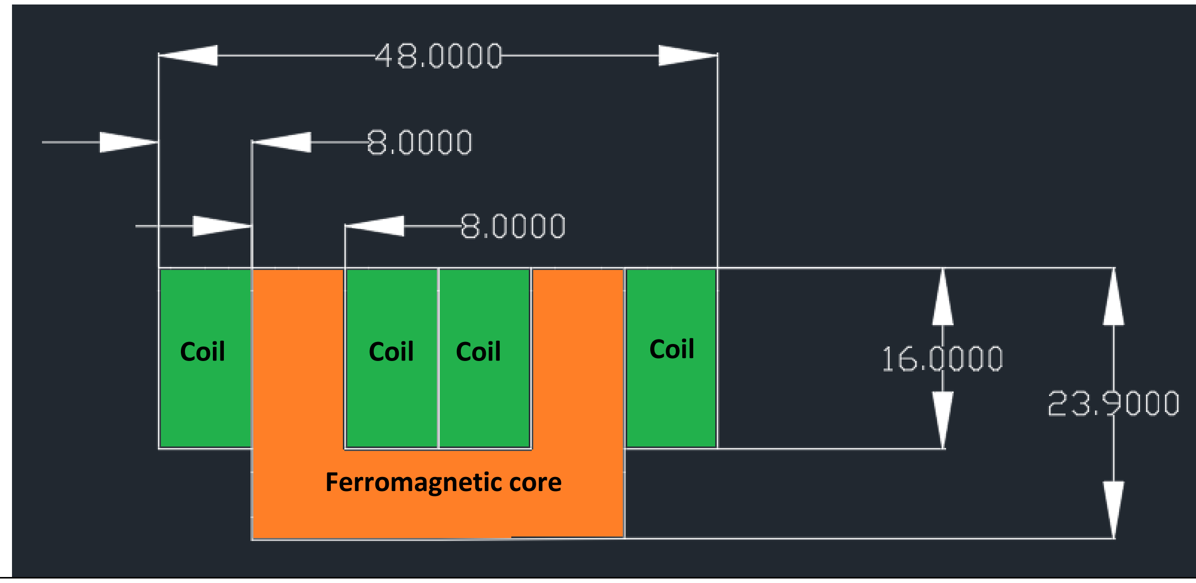
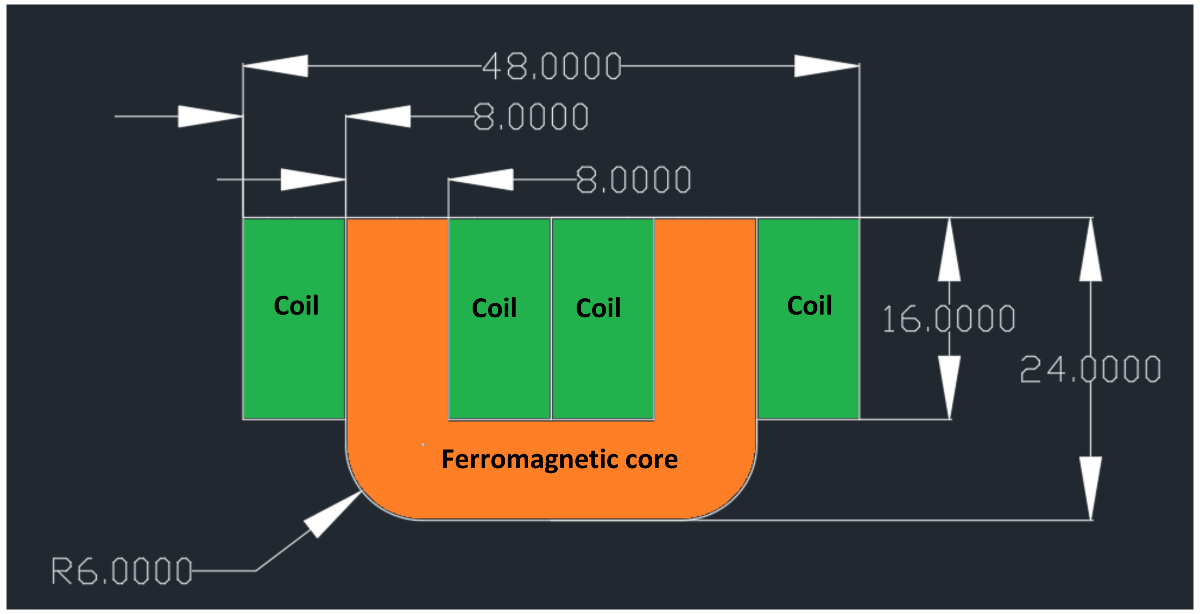
Appendix A - Investigated Shapes and Forces

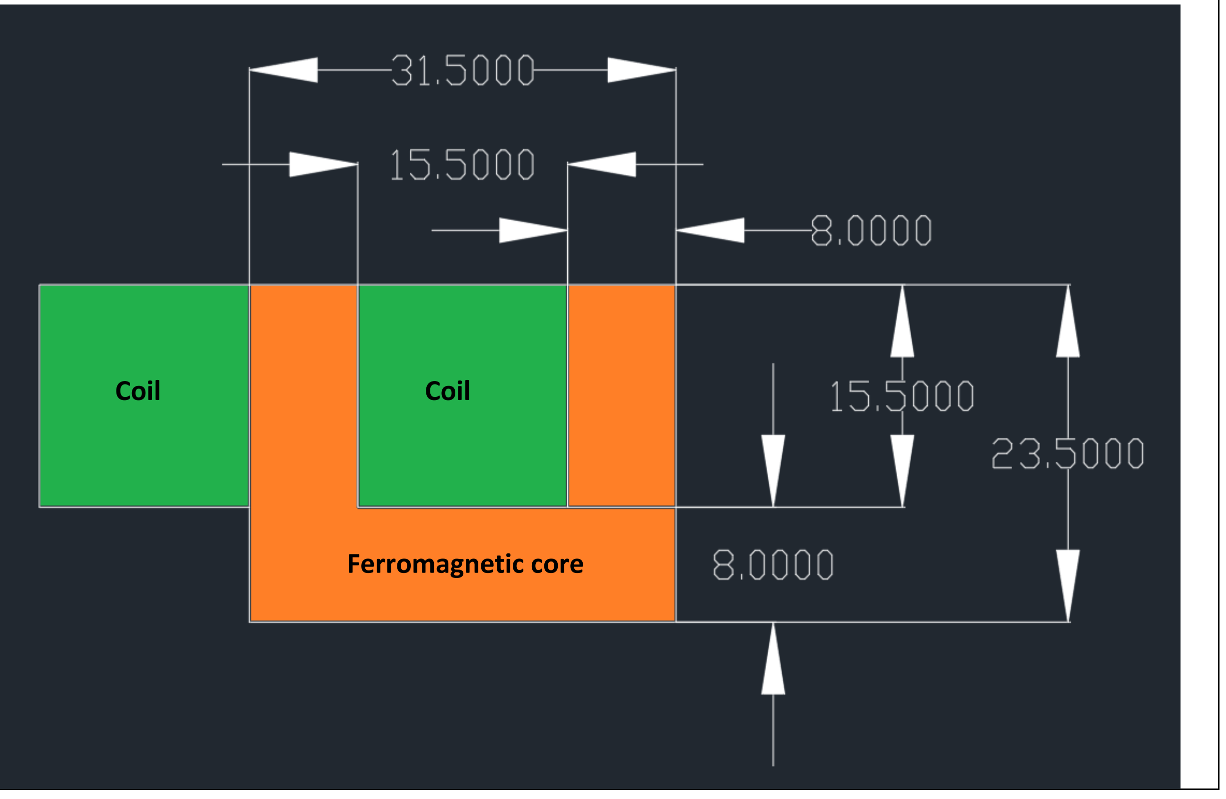
This section shows the shapes that was considered to maximise the opening and closing forces produced by the electromagnet while minimising its ferromagnetic core volume. The shapes presented on the table appear chronologically as they were considered. All measurements for opening and closing forces are conducted at 1400 A-turns at *20* °C. In Table A1 below, some comments are listed to show why some investigated shape are not chosen to pe presented to the client.

Table A1. Considered electromagnet shapes with the opening and closing forces measured at 1400-A turns with 2mm air gap at 20 °C.

Shape Number	Comments	Opening force (N)	Closing Force (N)	Holding force (N)	Ferromagnetic core Volume (cm^3)	Shape and Dimension – *all dimensions are in mm and degrees*
1	This shape was considered as the team was trying to imitate electromagnet shape advertised on Digi-key.	**5.57916**	**11.4287**	**2.3583**	**34.820**	

2	This shape was considered to improve shape 1 above.	**5.74092**	**10.3941**	**2.3781**	**27.714**	
3	This shape was considered to reduce core volume by reducing the width of the ferromagnetic core presented by the client. This shape improved the closing as well as the opening forces by 150% and 200% respectively. When investigating this shape, it was found that the closer the coil is to the permanent magnet, the higher the closing and opening forces.	**9.9**	**14.6**	**2.036**	**27.714**	

4	This shape has approximately 50% less volume than the client design. This shape also has 300% improvement over the client design for the opening forces and 160% improvement over the client design for closing forces at 1400 A-turn.	**13.9625**	**15.598**	**0.229**	**15.336**	
5	This shape was considered since it was observed that the magnetic flux is not present on the sharp corners. Thus, the corners at the bottom are shaved. This shape gave a lower volume over the unshaved corner version, but the opening force was decreases by approximately 0.5 N. The closing force remained approximately the same as the version without shaved corner. This shape was ultimately not chosen as it was rationalised that shaving the corners of the electromagnet could cost more if manufactured.	**13.915**	**15.5507**	**0.223**	**14.8962**	

6	This shape is the proposed shape to the client. It a slight variation of shape 4 above but it has a lower volume by 2.4%. Similarly, it also has higher opening and closing forces by 6.9% and 5% respectively. It was observed that with this configuration, shorter width of the electromagnet gives higher opening and closing force.	**14.93**	**16.39**	**0.220**	**15**	

Appendix B - BH curve data

The section shows the BH curve of the permanent magnet and ferromagnetic core under temperatures 0°C, 20°C, and 40°C. The corresponding magnetic flux density, B is estimated by having 1% increase for every 1°C decrease in temperature. The presented BH curves are used in FEMM software to evaluate the ferromagnetic core shapes that were investigated in Appendix A.

Table B1. BH Data at 0°C

Ferromagnetic Core		Permanent Magnet	
H (A/m)	B (T)	H (A/m)	B (T)
0	0	0	0
50	0.11736	50	0.1212
100	0.204	100	0.2376
150	0.2712	150	0.36
200	0.2988	200	0.4536
250	0.306	250	0.504
325	0.3144	325	0.516
400	0.31968	400	0.5184
475	0.32364	475	0.5196
550	0.32628	550	0.5208
625	0.32892	625	0.52116
700	0.3312	700	0.522

775	0.33288	775	0.52344
850	0.33552	850	0.52404
950	0.33816	950	0.52512
1050	0.3408	1050	0.52584
1150	0.34344	1150	0.52848
1250	0.3456	1250	0.52944
1350	0.348	1350	0.5304
1450	0.3504	1450	0.53064
1550	0.3528	1550	0.53076
3000	0.372	3000	0.552
5000	0.402	5000	0.5784

Table B2. BH Data at 20°C

Ferromagnetic Core		Permanent Magnet	
H (A/m)	B (T)	H (A/m)	B (T)
0	0	0	0
50	0.0978	50	0.101
100	0.17	100	0.198
150	0.226	150	0.3
200	0.249	200	0.378

250	0.255	250	0.42
325	0.262	325	0.43
400	0.2664	400	0.432
475	0.2697	475	0.433
550	0.2719	550	0.434
625	0.2741	625	0.4343
700	0.276	700	0.435
775	0.2774	775	0.4362
850	0.2796	850	0.4367
950	0.2818	950	0.4376
1050	0.284	1050	0.4382
1150	0.2862	1150	0.4404
1250	0.288	1250	0.4412
1350	0.29	1350	0.442
1450	0.292	1450	0.4422
1550	0.294	1550	0.4423
3000	0.31	3000	0.46
5000	0.335	5000	0.482

Table B3. BH Data at 40°C

Ferromagnetic Core		Permanent Magnet	
H (A/m)	B (T)	H (A/m)	B (T)
0	0	0	0
50	0.07824	50	0.0808
100	0.136	100	0.1584
150	0.1808	150	0.24
200	0.1992	200	0.3024
250	0.204	250	0.336
325	0.2096	325	0.344
400	0.21312	400	0.3456
475	0.21576	475	0.3464
550	0.21752	550	0.3472
625	0.21928	625	0.34744
700	0.2208	700	0.348
775	0.22192	775	0.34896
850	0.22368	850	0.34936
950	0.22544	950	0.35008
1050	0.2272	1050	0.35056
1150	0.22896	1150	0.35232

1250	0.2304	1250	0.35296
1350	0.232	1350	0.3536
1450	0.2336	1450	0.35376
1550	0.2352	1550	0.35384
3000	0.248	3000	0.368
5000	0.268	5000	0.3856

Appendix C - Key Calculations

This section shows the key calculations done to evaluate the proposed design's performance.

All calculations were done based on these parameters:

- Fixed supply voltage = 24V,
- Resistance of coil under 20 °C = 10 Ω.
- Number of turns of the coils = 900
- Cross sectional area of 900 turns coil of proposed design = 240.25mm^2

The equations below were used to estimate the current density in the coil, inductance in the ferromagnetic core, and time constant for current to increase or decrease in the coil.

Relationship between RMS current and duty cycle:

$$I = \frac{V}{R}\sqrt{D}$$

- V = Supply voltage (24V fixed)
- R = Coil resistance (temperature dependent)
- D = Duty cycle of supply voltage

Inductance in ferromagnetic core:

$$L = \frac{N\Phi}{I}$$

- N = number of turns
- Φ = flux measured across ferromagnetic core, due to permanent magnet and current through the coil
- I = RMS current in coil

Time constant:

$$\tau = \frac{L}{R}$$

- L = Inductance in ferromagnetic core
- R = Coil resistance (temperature dependent)

Table C1. The temperature effect on coil resistance (All About Circuits, n.d.)

Temperature (°C)	Coil resistance (Ω)
0	9.1918
10	9.5959
20	10
30	10.4041
40	10.8082

$$R = Rref[1 + \alpha(T - Tref)]$$

- R = conductor resistance at temperature "T"
- Rref = Conductor resistance at reference temperature Tref, at 20°C
- α = temperature coefficient of resistance for conductor material (in this case, copper = 0.004041)
- T = Conductor temperature in degrees Celsius
- Tref = Reference temperature that alpha is specified at for the conductor material

Example Calculations

For T = 0°C,

$$R = 10[1 + 0.004041(0 - 20)] = 9.1918\Omega$$

Table below shows the values of current density due to the changing duty cycle from 0.1 to 0.5 under 0 °C, hence coil resistance is 9.1918Ω.

Table C2. Current Density in coil vs Duty Cycle

Duty Cycle	Current as Duty Cycle	Total Amp-Turns	Current Density in A/m^2	Current Density in MA/m^2
0.1	0.83	743.11	3093070.28	3.09
0.2	1.17	1050.92	4374261.95	4.37
0.3	1.43	1287.10	5357354.88	5.36
0.4	1.65	1486.22	6186140.57	6.19
0.5	1.85	1661.64	6916315.41	6.92

Example Calculation

When Duty Cycle = 0.1

$$\mathrm{I} = \frac{\mathrm{V}}{\mathrm{R}}\sqrt{\mathrm{D}} = \frac{24}{9.1918}\sqrt{0.1} = 0.8256A$$

$$Total\ Amp - turns = 900 \times 0.8256 = 734.11A\ turn$$

$$Current\ Density = \frac{743.11}{240.25 \times 10^{-6}} = 3093070\mathrm{Am}^{-2} = 3.09MAm^{-2}$$

Note that the 0.5Ω shunt resistor mentioned in *Proposal to use the electromagnet for sensing* was not considered for the calculations. However, the trend of the forces on the permanent magnet due to the changing duty cycle should be similar.

Table C3 below shows the effect of the closing process on the force by decreasing the air gaps between permanent magnet and ferromagnetic core under 40°C, 0.5 duty cycle. The table also depicts the relationship between flux, inductance, and time constant. The flux is dependent on the distance between permanent magnet and ferromagnetic core and the RMS current flowing through the coils.

Table C3. Force vs Air gap

Air gap (mm)	**Flux (wb)**	**Coil resistance**	**I (A)**	**L (H)**	**Time constant**	**Force(N)**
22	8.89E-05	10.8082	1.5702	0.0510	0.00471	12.70
18	7.53E-05	10.8082	1.5702	0.0432	0.00399	3.94
14	6.91E-05	10.8082	1.5702	0.0396	0.00367	1.72
10	6.60E-05	10.8082	1.5702	0.0378	0.00350	0.91
6	6.41E-05	10.8082	1.5702	0.0368	0.00340	0.55
2	6.29E-05	10.8082	1.5702	0.0361	0.00334	0.37

Example Calculation

$$L = \frac{N\Phi}{I} = \frac{9008.90E - 05}{1.5702} = 0.05096\ H$$

$$\tau = \frac{\mathrm{L}}{\mathrm{R}} = \frac{0.05096}{10.8082} = 0.00471s$$

Force was measured in the FEMM software.