Jurnal
Teknologi

Full Paper

OPTIMIZATION OF THE FORCE CHARACTERISTIC OF ROTARY MOTION TYPE OF ELECTROMAGNETIC ACTUATOR BASED ON FINITE ELEMENT ANALYSIS

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Article history
Received
18 January 2016
Received in revised form
14 April 2016
Accepted
15 August 2016

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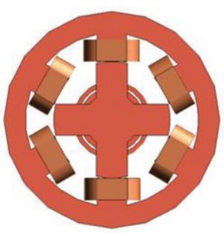
Graphical abstract



Abstract

This paper addresses a rotary motion type of electromagnetic actuator that compares two types of electromagnetic actuators; i.e the Permanent Magnet Switching Flux (PMSF) and the Switching Reluctance (SR) actuator. The Permanent Magnet Switching Flux (PMSF) actuator is the combination of permanent magnets (PM) and the Switching Reluctance (SR) actuator. The force optimizations are accomplished by manipulating the actuator parameters; i.e. (i) the poles ratio of the stator and rotor; (ii) the actuator's size; (iii) the number of winding turns; and (iv) the air gap thickness between the stator and rotor through Finite Element Analysis Method (FEM) using the ANSYS Maxwell 3D software. The materials implemented in the actuator's parameters optimizations are readily available materials, especially in Malaysia. The excitation current used in FEM analysis for both actuators was between 0A and 2A with interval of 0.25A. Based on the FEM analyses, the best result was achieved by the Permanent Magnet Switching Flux (PMSF) actuator. The PMSF actuator produced the largest magnetostatic thrust force (4.36kN) once the size is scaled up to 100% with the input current, 2A respectively. The maximum thrust force generated by the Switching Reluctance (SR) actuator was 168.85µN, which is significantly lower in compared to the results of the PMSF actuator.

Keywords: Electromagnetic, actuator, Finite Element Method, rotary motion

Abstrak

Kertas ini membentangkan penggerak elektromagnet jenis gerakan berputar yang membandingkan dua jenis motor; iaitu Magnet Kekal Beralih Fluks (PMSF) motor dan Pensuisan Keengganan (SR) motor. Pensuisan Fluks Magnet Kekal (PMSF), motor adalah gabungan Magnet Kekal (PM) dan Pensuisan Keengganan (SR) motor. Pengoptimuman daya dicapai dengan memanipulasi parameter penggerak; (1) Nisbah tiang daripada pemegun dan pemutar; (2) saiz penggerak; (3) bilangan penggulungan wayar; (4) ketebalan jurang udara antara pemegun dan pemutar; dan (d) melalui Finite Element Analysis (FEM) dengan menggunakan perisian ANSYS Maxwell 3D. Reka bentuk juga dibuat dengan menggunapakai material yang sedia ada di pasaran terutamanya di Malaysia untuk proses pengoptimuman. Arus yang disalurkan kepada penggerak adalah antara 0 dan 2 A dengan selang kenaikan sebanyak 0.25 A. Berdasarkan beberapa ujian, hasil yang terbaik yang telah dicapai adalah daripada Penggerak Pensuisan Magnet Tetap (PMSF). Ia telah menghasilkan magneto kuasa terbesar (4.36kN) apabila saiz dibesarkan dengan skala 100% dan jumlah arus yang digunakan adalah 2 A. Daya maksimum yang dihasilkan oleh penggerak Keengganan Pensuisan (SR) adalah 168.85μN yang mana sangat kecil berbanding dengan penggerak PMSF itu.

Kata kunci: Elektromagnet, penggerak, *Finite Element Method,* gerakan berputar

1.0 INTRODUCTION

Actuator is a device that generates thrust force or torque. An electromagnetic actuator is a device that converts an electrical input power to a mechanical output power, which consists of three main parts; i.e. (i) stator, which is the stationary part; (ii) rotor, which is the rotary part, and (iii) the winding armature, which is applied with excitation current.

The Switched Reluctance Motor (SRM) is one of the electromagnetic actuator, which was established in 1838. It has many advantages; i.e. low price, high robustness, able to operate in high temperature, and has high rotational speed [1], [2]. The advantage of the SRM actuator is that it does not consist of permanent magnets, which reduces the design complexity. SRM actuator has been widely used in home appliances such as air conditioners and vacuum cleaners. Moreover, it has been developed extensively around the world for automotive propulsion and pressure pump for industrial applications [3]–[5].

A Permanent Magnet Switching Flux (PMSF) actuator has a doubly salient structure and a magnet imbedded in each pole of the stator [6]. Therefore, it has the advantages of both the Switched Reluctance motor, but with permanent magnets. Moreover, in the PMSF actuator the magnetic flux always exists in the air gap and has a fixed magnetic field due to the permanent magnets. The rotor position that changes it's magnetic flux direction will cause variation in the motion direction and the amount of flux linkage in the stator coil, thus inducing the electromotive thrust force [7].

There are many types of rotary electromagnetic actuators; i.e. (i) Switched Reluctance (SR) actuator; (ii) Permanent Magnet (PM) actuator; and (iii) Permanent Magnet Switching Flux (PMSF) actuator. Table 1 summarizes the advantages and disadvantages of these electromagnetic actuators [7]-[9].

The torque expression is the key to understand the characteristics of an actuator. The torque of the electromagnetic actuator is derived from Equation (1), where the excitation current is an important variable to generate the torque [8]. Besides that, the position alignment of the rotor with respect to the stator position will affect the generate torque.

$$T_e = \frac{1}{2} i^2 dL\left(\frac{\theta, i}{d\theta}\right) \tag{1}$$

where:

- T_e =Electromagnetic torque.
- i =Excitation current.
- $L(\theta,i)$ =Inductance dependent on the rotor position and phase current respectively.

Based on previous research, in order to achieve a compact size to suit the home appliance applications [3]–[5], the outer diameter of the actuator should be less than 150mm. Several research have been done on evaluating the efficiency of the electromagnetic actuators through simulations and experimental works [10]–[13]. Currently, the SR actuator is highly demanded in manufacturing production due to its advantages [1], [2]. By adopting the readily available materials, would improve the marketing quality of SR actuator. Therefore, in this paper the materials of the actuator used in FEM analysis are among the materials that are easily obtain for fabrications purpose & for further research work.

In Japan, abundant researches were done on design optimization before fabricating the prototype in order to develop high efficient actuators. One of the method is diversifying the actuator's parameters. Rather than designing a new types of actuator, these researches focus on improving the conventional actuators [8], [14]–[16]. Thrust force optimization process often involved the actuator parameters that are being varied [17]–[20]. The performances of the actuator are evaluated by varying the poles number of the conventional actuator [15]. Besides that, in [8], the optimization process was made by varying both the materials and the number of poles. In [8] the focus was to compare the efficiency of the SR actuator and the Interior Permanent Magnet Synchronous Motor (IPMSM). The experimental works have shown that the maximum torque achieves by SR actuator was competitive with the IPMSM after increasing the number of poles.

Therefore, in this paper the objective is to evaluate the optimized thrust force characteristics by varying the actuator parameters. The optimized thrust force is the highest thrust force generated by the design being evaluated using FEM analysis, with the advantage of readily available materials in Malaysia. The simulations through Finite Element

Analysis (FEM) were done by using ANSYS Maxwell 3D software to verify the static thrust force. The optimized actuator parameters will next be used for future fabrication and experimental works.

In Section 2, this paper will discuss the initial geometric design and the parameters to be varied. In Section 3, the generated thrust force using the FEM analysis are discussed. The last section will conclude the chosen actuator parameters of the PMSF actuator and SR actuator configurations based on the optimized thrust force characteristics.

Table 1 Comparison of SR, PM and PMSF actuator

Motor Type	Structure	Torque	Input Power	Robustness
Switched Reluctance (SR)	Simple	High	Large	High
Permanent Magnet (PM)	Simple	High	Small	High
Permanent Magnet Switching Flux (PMSF)	Simple	High	Small	High

2.0 METHODOLOGY

In this paper, there are two types of rotary electromagnetic actuators that will be evaluated; i.e. Permanent Magnet Switching Flux (PMSF) and the Switching Reluctance (SR) actuator. The analyses were done through FEM analysis to obtain the optimized thrust force characteristic. The actuator parameters that are a concerned in this paper are, i.e. (i) stator-to-rotor (S:R) poles ratio; (ii) actuator's size; (iii) number of winding turns; and (iv) air-gap thickness. Finally, either PMSF or SR actuator with the highest thrust force characteristics will be concluded as the optimized thrust force based on the parameters optimizations.

The ANSYS Maxwell 3D software is used to draw, design and analyze the thrust force of the electromagnetic actuator. ANSYS Maxwell 3D is a high performance interactive software package, which uses Finite Element Analysis (FEM) to solve the magnetic, electric, eddy current and transient problems for electric machines.

Based on Equation (1), the force characteristic may show different force characteristic for every configured material and parameters. The thrust force characteristics of electromagnetic actuator significantly depended on the excitation current that flows through the coil. Equation (1) shows that the electromagnetic torque is proportional to the amount of excitation current. In this paper, the excitation current was varied from 0A to 2A with interval of 0.25A in order to evaluate the thrust force characteristics.

2.1 Design Structures: Permanent Magnet Switching Flux (PMSF) and Switched Reluctance (SR) Actuator

Table 2 shows the two types of the actuator that were designed with their initial parameters, respectively. In this paper, the parameters being varied have limitations due to its compact size, which is the main focus of this study. Figure 1 and Figure 2 show the design of PMSF and SR actuators; i.e. top view, side view and isometric view which comprise of six (6) stator poles and five (5) rotor poles, i.e. S:R ratio is 6:5. The difference between the PMSF and SR actuator is the presence of permanent magnets in the PMSF actuator, as shown in Figure 1. In the next sections, to discuss the varied parameters, only the geometric design for PMSF actuator are shown; i.e. Figures 3 to 6. The similar method to vary the parameters is also applicable for the SR actuator. Similar parameters of the PMSF and SR actuator will be varied in order to analyze the thrust force characteristics.

The operation of the actuator relies on the 3 phase excitation current applied to the actuator as shown in Figures 1 and 2. The stator poles are connected in an alternative sequence with three electrical phases; each phase activates a group of stator independently as shown in Table 3. When a phase is activated, magnetic flux flows through the corresponding stator and rotor pair thus generating the rotary motion.

Table 2 Initial Parameter of the PMSF and SR actuato r

Parameters	Value	
	PMSF	SR
Stator outer diameter, D_o	60 mm	
Stator inner diameter, D_i	36 mm	
Air gap thickness, G	0.1 mm	
Winding number	100 Turns	
Stator and rotor height, H	36 mm	
Stator-to-rotor number	6:5	
Permanent Magnet	Available	Not available

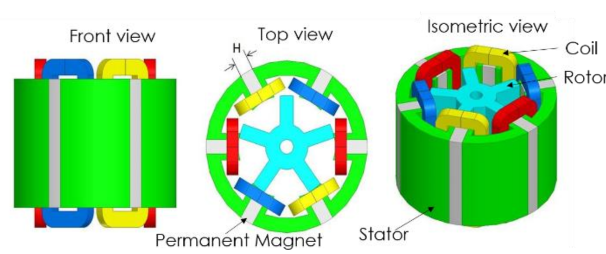


Figure 1 Initial design of PMSF actuator

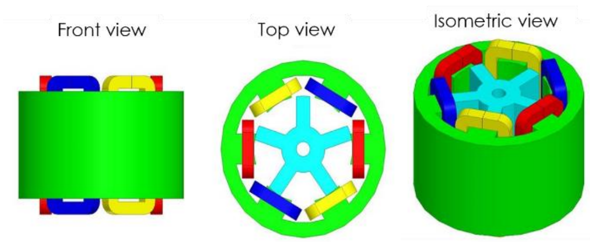


Figure 2 Initial design of SR actuator

Table 3 Label of PMSF and SR actuator

Part	Label
Phase A	(red)
Phase B	(yellow)
Phase C	(dark blue)
Stator	(green)
Rotor	(light blue)
Permanent Magnet	(grey)

2.1.1 Varying the Stator-to-Rotor (S: R) Poles Ratio

In order to optimize the thrust force characteristics, one of the parameters that gave effect to the thrust force is the poles ratio of stator and rotor (S:R). In this section, the S:R poles are varied, while the other actuator parameters are fixed based on Table 2. Initially, the number of S:R poles ratio is fixed to 6:5 ratio for both designs, based on previous research [17]. Then, the S:R poles ratio of both actuators were varied to three values; i.e 6:5, 12:10 and 18:16 respectively as shown in Figure 3, whilst the air gap between the stator-rotor, winding number and stator outer diameter is fixed to 0.1 mm, 100 turns and 60 mm, respectively. The FEM analysis was implemented by applying excitation current to the actuator; i.e. from 0A to 2A with interval of 0.25A.

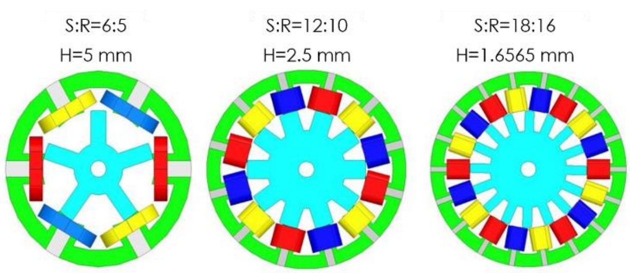


Figure 3 PMSF design with vary S: R ratio

2.1.2 Varying the Actuator's Size

The size of the actuator was scale to six values; i.e. from 0% (original size) to 100% respectively, with an interval of 20%. The air gap between the stator-rotor, winding number and S:R ratio is fixed to 0.1 mm, 100 turns and 6:5 poles ratio, respectively. The size of the actuator was only increase up to 100% due to the limitations of the dimensions based on applied application. Figure 4 shows the top view of the PMSF actuator designs with varying sizes.

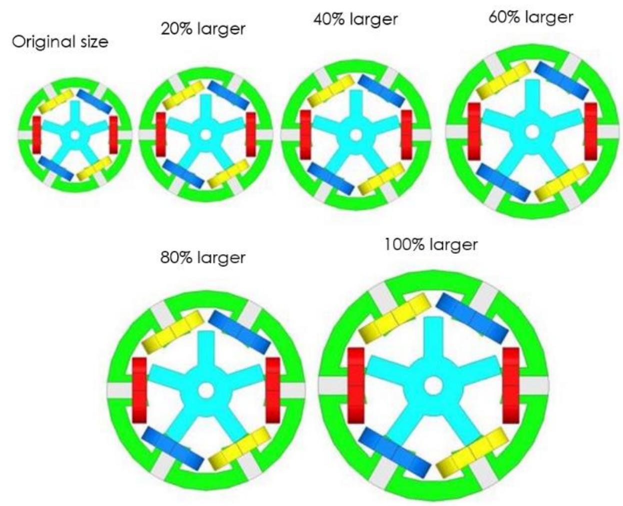


Figure 4 Vary size of PMSF actuator

2.1.3 Varying the Number of Winding Turns

The number of winding turns was varied to six values; i.e. from 100 turns to 200 turns respectively, with an interval of 20 turns in each coil. The air gap, G between the stator-rotor, stator outer diameter and S:R ratio is fixed to 0.1 mm, 60 mm and 6:5 poles ratio, respectively. Further increased of winding turns was not evaluated due to the space limitations for applied application. Figure 5 shows the isometric view of the coils when the number of winding turns is varied.

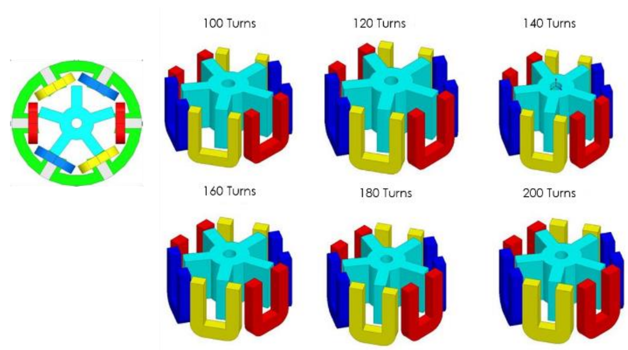


Figure 5 Vary number of winding turns

2.1.4 Varying the Air Gaps Thickness between Stator and Rotor

The air gap plays an important role in generating high thrust force. The initial air gap of the designs is 0.1 mm. In the FEM analysis, the air gap, G was varied to five values; i.e. from 0.1 mm to 0.5 mm, with an interval of 0.1 mm. Figure 6 shows the zoomed top view of the air gap; i.e. 0.1 mm thickness between the stator and rotor.

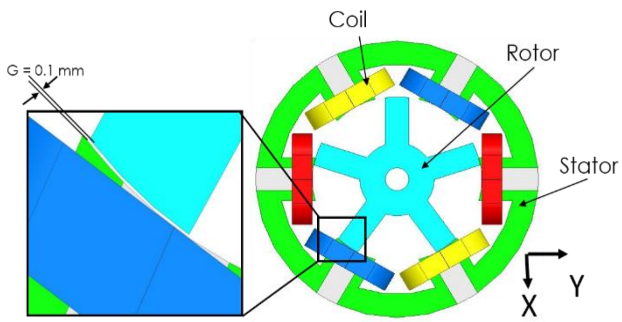


Figure 6 Zoom top view of 0.1 mm air gap thickness for the PMSF actuator

2.1.5 Materials of the Actuators

The electromagnetic actuator has simple structure which consists of three types of materials. In the FEM analysis, the assigned materials are important to determine the permeability of the actuator towards the formation of magnetic flux. Table 4 shows the material used in FEM analysis for PMSF and SR actuator. The chosen materials were based on its availability in Malaysia's market.

Table 4 Materials of PMSF and SR actuator

Part	Material	
	PMSF	SR
Stator core	Iron	
Rotor core	Iron	
Coil winding	Copper	
Permanent Magnet	NdFe3	Not available

The stator core and rotor core materials are using iron. Iron is widely used in actuators, generators, and other industrial applications. Iron was selected, because it is low cost, extremely robust, and easy to be shaped into different forms. It also has high permeability that allow flows of magnetic flux [21]. The permanent magnet material used in the PMSF actuator stator poles is NdFe35, which is an alloy made of neodymium and iron. This type of magnet was chosen due to its advantages, which are low cost, high coercive thrust force, and high resistance to corrosion. Copper wire is used as the coil winding for both actuators due to it high conductivity.

3.0 RESULTS AND DISCUSSION

The Finite Element Analysis Method (FEM) was used to optimize the thrust force characteristics. The optimize thrust force were obtained by varying the parameters as discussed in Section 2, i.e; (i) stator-to-rotor (S:R) poles ratio; (ii) actuator's size; (iii) number of winding turns; and (iv) air-gap thickness.

3.1 Effect of Poles Ratio of Stator and Rotor (S:R)

The effect of varying the S:R poles ratio are shown in Figures 7 and 8. From Figure 7, it can be depicted that the PMSF actuator with S:R = 6:5 poles ratio produces larger thrust force than S:R = 12:10 and 18:16 poles ratio. Increasing the S:R poles ratio for the PMSF actuators will reduce the surface region of the poles, thus decreasing the thrust force thus the . This is because the generated magnetic flux will have a tight area to pass through between the stator and rotor poles. Meanwhile, from Figure 8, increasing the poles ratio for the SR actuator increases the thrust force. The SR actuator with S:R = 18:16 poles ratio produces larger thrust force than S:R = 6:5 and 12:10 poles ratio. Since the SR actuator does not implement any permanent magnets, thus the generated magnetic flux was small and sufficient to pass through the tight area. The high number of poles-per-phase helps smoothen the rotations in compared to lower S:R poles ratio.

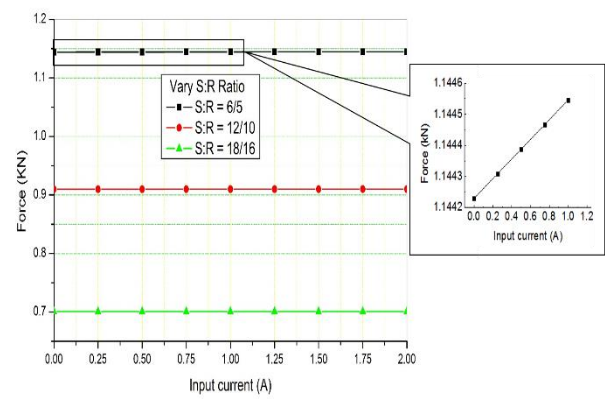


Figure 7 FEM result with varying S:R poles ratio for PMSF actuator

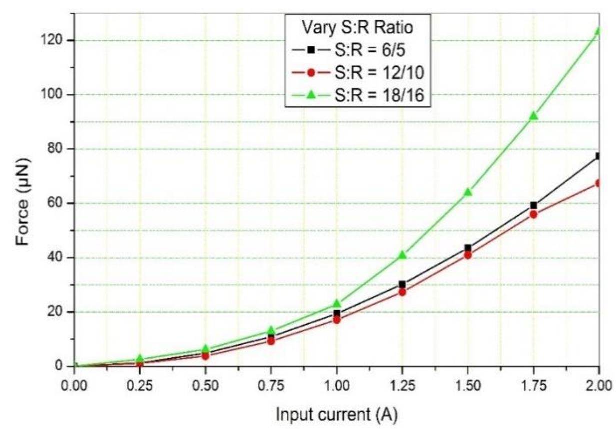


Figure 8 FEM result with varying S:R poles ratio for SR actuator

3.2 Effect on Actuator's Size

Figures 9 and 10 show the relationship between the actuator size and the generated thrust force when current was excited from 0A to 2A for both designs. From Figure 9, it can be depicted that increasing the size of the PMSF actuators causes an increase in the magnetostatic thrust force. It can be seen that 100% scaling gave the highest thrust force; i.e 4.36kN.

In comparison, Figure 10 shows the thrust force for the SR actuator. It can be depicted that once the size scaled reached 20%, the thrust force decreases drastically when applying the 40%, 60%, 80% and 100% scaling factors. The reason is that the SR actuator does not have enough magnetic flux generated by the input excitation current, in compared to PMSF actuator that has the advantages of both the permanent magnets and input excitation current. Therefore, for the SR actuator any increase in the size will cause decreases in the actuator's thrust force.

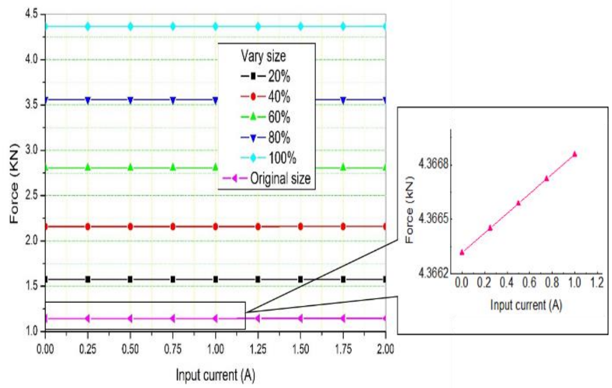


Figure 9 FEM result with varying the size for PMSF actuator

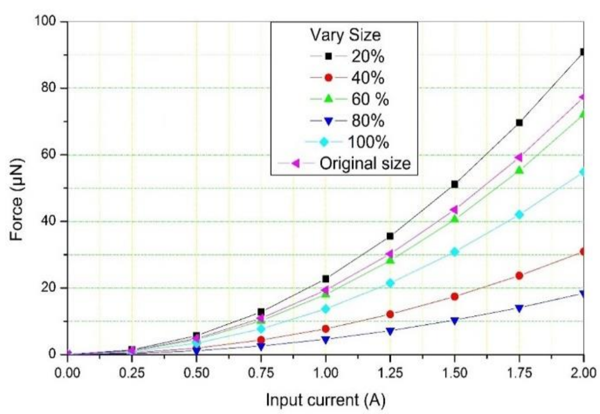


Figure 10 FEM result with varying the size for SR actuator

3.3 Effect of Winding Turns

Figures 11 and 12 show the relationship between the winding turns and the generated thrust force when current was excited from 0A to 2A for the PMSF and SR actuator. From Figure 11 & 12, it can be depicted that as the winding turns increase in the SR actuator, the thrust force will also increase with the excitation current. However, for the PMSF actuator, the increment in the thrust force does not show significant changes as compared to the SR actuator, depicted in Figure 11. This is due to the high accumulates magnetic flux generated by the combinations of permanent magnet flux and electromagnetic flux which leads to saturations levels for all of the winding turns. Therefore, it can be concluded that the generated thrust force depends on winding turns for both designs, however for the PMSF actuator, the permanent magnet significantly affect the thrust force which leads to saturations.

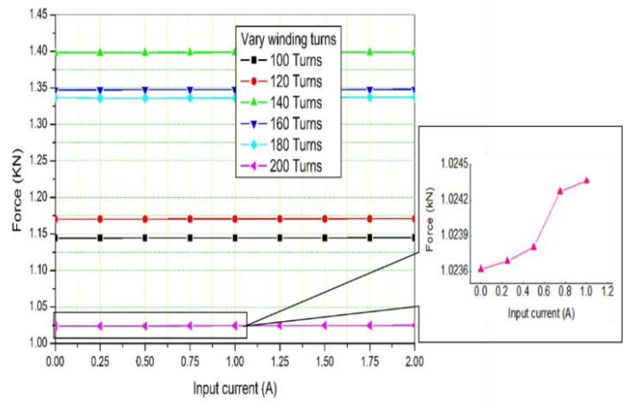


Figure 11 FEM result with varying winding turns for PMSF actuator

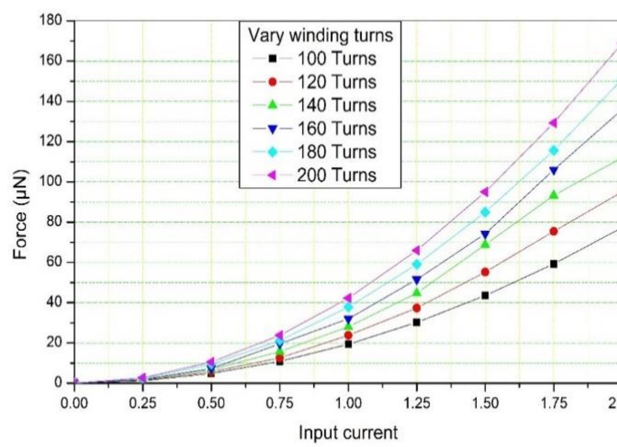


Figure 12 FEM result with varying winding turns for SR actuator

3.4 Effect of Air Gap Thickness

Figures 13 and 14 show the relationship between the air gap and the generated thrust force when current was excited from 0A to 2A for both design. It can be depicted that the smaller the air gap thickness between stator and rotor, the greater the output thrust force generated by the actuators. For an electromagnetic actuator, the magnetostatic thrust force is influence by the reluctance of the air gap. Larger air gap tends to have high reluctance and thus decreasing the generated thrust force. The effect of the permanent magnet (PM) in the PMSF actuator is also important which should be taken into account. In Figure 13, for the PMSF actuator, even though the excitation current is 0A, the thrust force is still being generated by the permanent magnet; i.e. generated thrust force is 1.14 kN for 0.1 mm air gap. In compared to the SR actuator as shown in Figure 14, the highest magnetostatic thrust force (77.35 µN) is produced by the smallest air gap, 0.1mm once the input excitation current is at 2A.

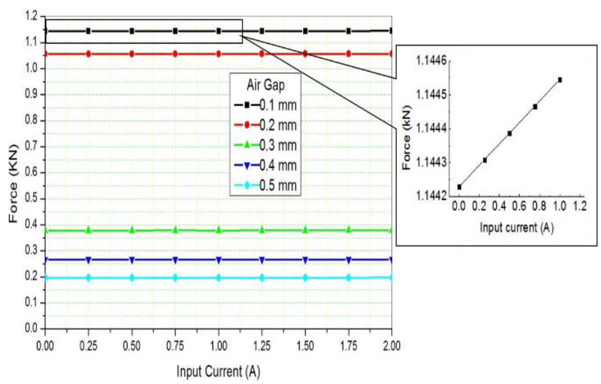


Figure 13 FEM result with varying air gap, G for PMSF actuator

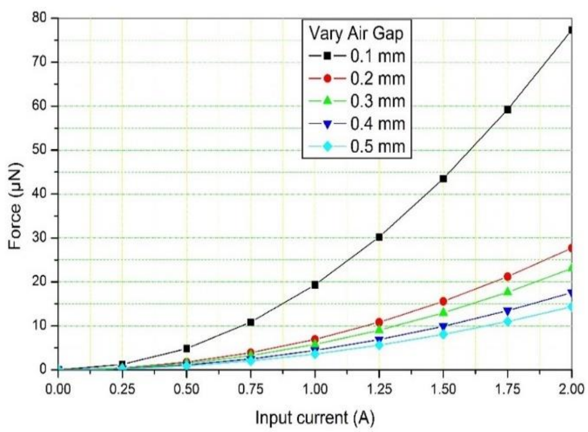


Figure 14 FEM result with varying air gap, G for SR actuator

3.5 Optimized Actuator Parameters Based on FEM Analysis

The optimization of the thrust force was done for PMSF actuator and SR actuator using FEM analysis in the previous sections. Based on the FEM analysis, it can be concluded that the thrust force generated by the actuators increases as the excitation current increased. This complies with Equation (1), where the value of torque is proportional to excitation current. Table 5 shows the optimize actuator parameters which was achieved by the PMSF actuator (highest thrust force = 4.36kN) when the size was scaled up to 100%; number of winding turns is 100 turns; S:R = 6:5 poles ratio and air gap thickness is 0.1mm, respectively.

Table 5 Summary of the optimized thrust force, with 2A excitation current

No.	Varying Parameter	Designs	
		PMSF	**SR**
1	Actuator's size	100% larger	Original size
2	Number of winding turns	100	200
3	S:R poles ratio	6:5	6:5
4	Air gap thickness	0.1mm	0.1mm
	Maximum thrust force	**4.36kN**	**168.85µN**

4.0 CONCLUSION

Two types of electromagnetic actuators; i.e. the Permanent Magnet Switching Flux (PMSF) flux and Switching Reluctance (SR) actuator have been designed and analyzed by using Finite Element Analysis (FEM). As shown in the methodology section, four (4) actuator parameters were varied; i.e. (i) stator-to-rotor (S:R) poles ratio; (ii) actuator's size; (iii) number of winding turns; and (iv) air-gap thickness. The FEM analysis results clarifies that the Permanent Magnet Switching Flux (PMSF) actuator shows a better performances in term of thrust force characteristics, with the generated thrust force of 4.36kN. Thus, as a conclusion, the parameters of PMSF actuator will be the selected design for future research works.

Acknowledgement

Authors are grateful to Universiti Teknikal Malaysia (UTeM) for supporting the research. This research and its publication are supported by Research Acculturation Collaboration Effort (RACE) no. RACE/F3/TK5/FKE/F00249.

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