Design a Slot-Less Linear Actuator for Food Processing Application

R.N. Firdaus[1], S. Zulaika[1], K. Kamalia[1], R. Suhairi[1,2], M.Z. Aishah[1], M.N. Othman[1], A. Khamis[1]
[1]*Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Malaysia.*
[2]*Electrical Technology Section, Universiti Kuala Lumpur-British Malaysian Institute, Malaysia.*
norfirdaus@utem.edu.my

***Abstract*—This paper is about design of slot-less linear oscillatory actuator for food processing application. Linear actuator is a device that produces linear motion without using any mechanical. People are still using traditional or conventional compression method by pressing hand in the moulding device to process the traditional cookies such as samperit and tart. However, this method is no longer practical as it requires a lot of energy and longer time to press the dough which will affect the productivity. The main objective of this research is to design slot-less linear actuator for food processing based on desired application. So, a power moulding device embedded with slot-less linear actuator is proposed and simulated using Ansys Maxwell software. In Ansys Maxwell, the analysis of the coil sizing has been carried out in details. The variable parameters that include in this project are number of coil, number of turns, height of coil and gap between coils. As a result, the best model of slot-less linear actuator is chosen based on the required specifications and thrust characteristic. This new device can help to overcome or solve the weaknesses of the conventional compression method. In conclusion, this research provides overview and guidelines of linear actuator for food processing.**

***Index Terms*—Slot-Less Linear Oscillatory Actuator; Linear Motion.**

I. Introduction

Linear actuator is a device that produces linear motion directly without using any mechanical transmission to convert rotary motion to linear motion [1]. Linear actuator is widely used in power generation sector, factory automation sector and as well as in household appliances. Slot-less type stator is the stator that has stator yoke without stator tooth. The coil in the slot-less type stator is wound around cylindrical shape.

For over so many years, peoples are still using conventional compression method by pressing hand in the moulding device but this no longer practical because it requires human energy and less productive when handling larger amount of dough. Entrepreneurs will face difficulties when handling large amount of order from their customers. Furthermore this method is poor in cleanliness aspect because frequent hand contact with the dough itself and improper handling of the devices. To overcome the problems, a proper moulding device that can increase the productivity, safe to handle and have high cleanliness level should be introduced.

Several related research were conducted in order to determine the thrust characteristics of the linear actuator. In research entitle thrust characteristic of double side plate permanent magnet linear synchronous motor for EML system by [4] they analyzed the thrust characteristics in different conditions including the length of air gap. It was mention that, as the air gap increased, the mean thrust is linearly reduced and the thrust ripple decreased. Besides, it also mentioned that the air gap flux density and the thrust increase as the current increases.

Another research entitles thrust analysis and measurement of tubular linear actuator with cylindrical halbach array by [5] discussed about the prediction of the thrust characteristics according to the design parameter such as the magnet height, air gap length, coil thickness and poles numbers. Halbach magnetized mover has inherent self-shielding property and thereby did not need back iron [5]. The halbach array has a simple control structure due to the sinusoidal form of magnetic field produced. The chosen type of stator is the slot-less stator because it can eliminate the cogging effect, thus improved the dynamic performance and servo characteristics [5]. It can be concluded that, the variations of thrust is affected by the air gap length.

Next in research entitle the starting thrust simulation of a tubular linear motor (TLM) by [6] concluded that TLM can provide high instantaneous starting thrust as it acts as pushing motor [6]. There are several advantages of the tubular motor which are; it has a simple structure, no widthways end-effect and larger thrust of force. It was mentioned that the air gap is a very important electromagnetic parameters which can affect the output performance, the difficulty of processing and the costs of productions [6]. The smaller the primary tooth is, the larger the fluctuations of the thrust.

Other study on the related research is about linear oscillatory actuator using new magnetic movement characteristic by [7] which employing dc motor and Magnetic Movement Converter (MMC) to clarify that the thrust and the armature position characteristic of the new magnetic movement has fewer harmonic and load torque of dc motor can be reduced [7]. It had been conclude that, the proposed actuator has smaller torque than the conventional actuator. It also has constant static current even when the armature moved [7]. This new MMC uses lower power and smaller dc motor can be used as it does not generate high load torque [7].

Next in another related research entitle comparison on thrust characteristic of linear oscillatory actuator (LOA) by Norhisam M et. al [8]. This research focused to analyze the thrust characteristic for two types of LOA in term of the characteristic of voltage, coil current, number of winding and force. It was mentioned that the flux will flowing from the permanent magnet through moving yoke, air gap and outer yoke before it return to the permanent magnet. The highest flux line is at the first coil of moving magnet. It has been confirmed that high taper, air gap taper and thickness of the tapper are the principal parameters that can influence the optimum length [8].

In addition, the next research entitles the influence of mechanical springs on dynamics performance of moving magnet linear actuators with cylindrical halbach array by Seok-Myeong Jang et. al [12] which describe the influence of mechanical springs on the dynamics performance of a moving-magnet linear actuators with cylindrical halbach array. Based on the result obtain [12] improvement of dynamic performance a linear actuator should be equipped with a spring and should be driven at the resonant frequency which can be adjusted properly by varying the value of coefficient of elasticity of spring. The advantages of using halbach array as a mover and slot-less type as a stator of the moving-magnet linear actuators because the fundamental field of the halbach array is stronger by 1.4 compared to conventional array and the power efficiency is doubled.

Based on the related research entitle a proposal of small linear actuators for small entertainment robots by Yasuaki et.al [13] proposes a linear actuators consisting of a DC motor and pair of spiral spring and cylinder. The advantage of the structure proposes is it brings flexibility of the actuators. Based on the experiment conducted, the inconstant actuation of them in the same situation and the amount of changing at elongation or contraction for the time when the actuator is driven.

Based on the previous research above, the higher thrust can be obtained by considering the interaction between the parameters includes such as magnet and coils. The air gap and the material used for each parameter are very important to control the thrust. Therefore, investigation of coil sizing is important since it could effects the thrust. So, this paper analyzes the coil sizing that suitable for designing this linear actuator for food processing applications.

II. BASIC STRUCTURE OF SLOT-LESS LINEAR ACTUATOR

To overcome the problem of the conventional devices, the slot-less linear actuator is introduced. The concept of the electrical moulding device with slot-less linear actuator for food processing application is shown in Figure 1. As power is applied to the slot-less linear actuator, the mover will compress the dough inside the chamber to produce desired shape of dough. The mover is made up from permanent magnet which will be sealed by mover casing that made up from non-ferromagnetic material such as plastics to avoid contact and dough isolation. This technique is more practical since it use less human energy and less hand contact with dough. So, cleanliness should not be an issue. The productivity also will increase as this device can handle a larger quantity of dough. The density of the dough whether the dough is hard or soft is also will be considered in this project.

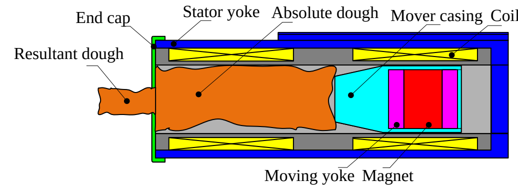

Figure 1: The slot-less linear actuator.

The advantages of this new linear actuator compared to the conventional actuators are it has a simple structure, better dynamical performance and have higher reliability. It also able to work at high speed and high efficiency. This new devices is user friendly because it does not require human energy to press the dough and also no contact with human body.

III. ANALYSIS PARAMETER

Figure 2 shows the overall process of this research until the desired specification of the linear actuators is obtained. To get the best result, the declaration of the analysis parameter is carried out which is suitable for this project. There are certain parameter that has been finalized to be fixed such as size of magnet, stator, moving yoke and number of moving yoke. The other parameter is varied while doing this analysis. After the analysis of coil sizing is done and the best result is obtained, the model has been selected as the chosen model for this project.

Based on the specifications such as height and the diameter of the device, the volume of dough that can be filled in the moulding device is estimated. Besides, the force needed for the plunger to push the dough is also determined. The actuator model needs stator and coil that act as the chamber and moving yoke and magnet act as plunger in traditional moulding device. Table 1 shows the specification of the linear actuator for this research. The minimum target thrust for the linear actuator is 40 N, the target displacement for the plunger to move is 40 mm and the width of stator is fixed to 183 mm. Figure 3 shows the design specification of the linear actuator.

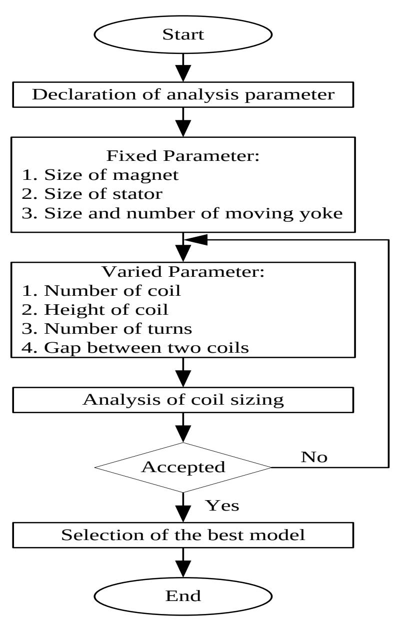

Figure 2: Flowchart of the analysis

Table 1
Specification of the linear actuator.

Target		Values
Minimum Thrust	[N]	40
Minimum Displacement	[mm]	70
Width of the stator	[mm]	183

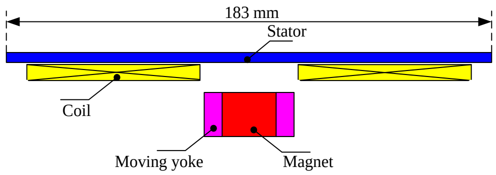

Figure 3: Design specifications

Figure 4 shows the expected thrust characteristic for the desired electrical moulding devices. The operating displacement, xop is basically the maximum range of displacement that will compress the dough at minimum thrust of 40 N. The minimum operating displacement for this device is 40 mm which is 35 mm from the negative polarity and 35 mm from the positive polarity at the minimum thrust, 40 N. The polarity shows the different polarity of the mover moves and zero at the center is when the mover is at the center of the actuator.

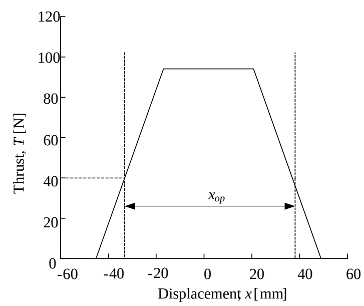

Figure 4: The expected thrust characteristic.

By using Ansys Maxwell software, the flux lines and flux density of the designed actuator can be determined. The flux lines are determined to show the direction of the flux which is from the north poles to the south poles. The designed actuator should meet the requirement of the flux density not more than 1.5 T [11].

Result of force versus moving position or displacement is plotted. If the result is not satisfied the desired result, certain parameters need to be adjusted in the Ansys Maxwell software. These processes are repeated until the desired waveform comes out and the design satisfied the specifications needed.

These include size of the stator, size of magnet, size of moving yoke and width of the coil. Meanwhile, Table 2 shows the variable parameter for density of the motor. The variable parameters are number of coil, number of turns, height of coil and gap between coils. When the height of the coil has been determined, the number of turns also can be calculated. The number of turns is depends on the size of the coil with the coil wire diameter. The calculation of number of turn can be defined as Equation 1.

$$N = \frac{w_c}{d_c} \times \frac{h_c}{d_c} \tag{1}$$

whereas, w_c is the width of coil [mm], h_c is the height of coil [mm], d_c is the diameter of coil and N is the number of turns. The gap between two coils is varied to obtain longer operating displacement between two coils. Lastly, selection can be made based on the result obtained.

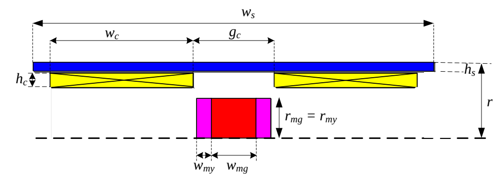

Figure 5: The parameters in structure modeling of the linear actuator

Table 2
Fixed parameters

Element	Value (mm)
Size of stator yoke, w_s	183
Height of stator yoke, h_s	4
Width of magnet, w_{mg}	20
Height of magnet, r_{mg}	15
Width of moving yoke, w_{my}	8
Height of moving yoke, r_{my}	15
Width of coil, w_c	65
Diameter of the coil wire	0.5
Radius, r	35
Number of coil	2

IV. ANALYSIS OF THE COIL SIZING

A. *Simulation Result for Coil*

Figure 6 shows the initial result of the linear actuator. The height of the coil is changed from 4 mm to 8 mm and the width of the coil is fixed to 65 mm for one coil. Based on the result, the highest thrust of the model is approximately 160 N using 8 mm height of coil. At minimum thrust, 40 N, it produces the longer operating displacement, x_{op} approximately 70 mm compared to the other height of coil. The bell shape graph of thrust versus displacement is obtained. The plunger will move until it reached the peak value of thrust at the centre and dropping slowly as the value of thrust is decreasing. The design model is closed to the expected thrust characteristic but there is no constant value of thrust obtained as it produces a peak value of the thrust.

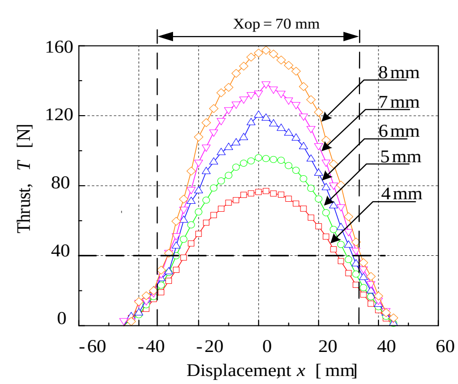

Figure 6: Initial Result of linear actuator model.

B. Simulation Result of Gap between Coils

In order to obtain longer constant thrust, the gap between coils is changed from 31 mm to 37 mm. The height of coil chosen is 8 mm. This is because based on the Figure 6 it is produce the highest thrust that is approximately about 160 N compared to others. The result of the gap between two coils is shown in Figure 7**.** It can be seen that for the gap of 31 mm the target minimum operating displacement that is 40 mm is achieved and this model produced longer operating displacement which is 70 mm. The thrust is almost constant at -35 mm to 35 mm compared to other size of gap. By this, the plunger will received a constant force for 70 mm before its drop. So, this model achieved all the target of the expected thrust characteristic and also fulfilled the specification of the designed linear actuator. The best gap chosen is 31 mm between coils at the height of 8 mm.

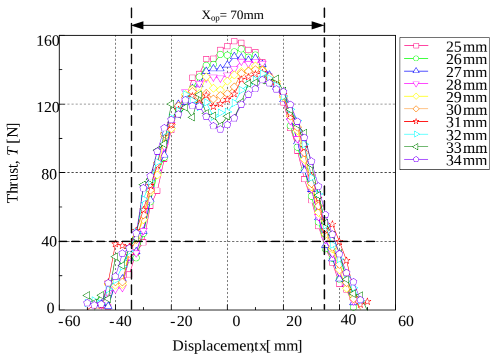

Figure 7: Result analysis for gap between coils

C. Simulation Result of the Performance Characteristic

Based on the previous result of the gap between two coils, the best model chosen is the height of the coils which is 8 mm and gap 31 mm. Figure 8 shows the performance current characteristic of the chosen model linear actuator. The current applied are 2 A, 4 A and 6 A. The current of 6 A, produce the highest thrust compared to other values of current.

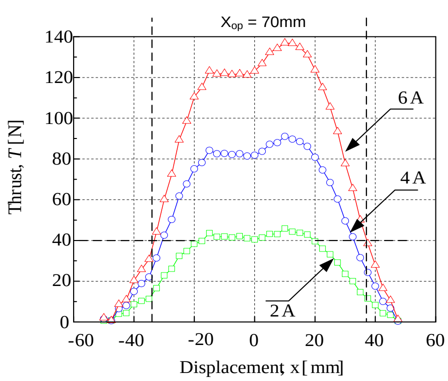

Figure 8: Performance current characteristic.

V. THE FINAL DESIGN OF LINEAR ACTUATOR

Figure 9 shows the specification of the final design of the linear actuator that has been chosen based on the analysis. Meanwhile, Figure 10 shows the cross-sectional view of the linear actuator. The design of the linear actuator consists of stator yoke, two coils, single magnet and two moving yoke. The moving yoke and magnet are attached together and is placed in the mover case. The mover case will act as the plunger. The dough will be compressed and the desired shape of dough will comes out at the end cap. The material of the stator and moving yoke in the simulation is steel, while the coil and magnet are made from copper and NdFe35 respectively. In the simulation by using Ansys Maxwell software, the electromagnetic gap for this design is 2.5 mm but it has mover case that acts as air as it uses aluminum material. So, the mechanical air gap is 0.5 mm. The width of coil is 65 mm with the height of coil is 8 mm. The number of turns calculated for this model is 2080 with the coil diameter of 0.5 mm. The gap between coils is 31 mm and the current applied is 6 A.

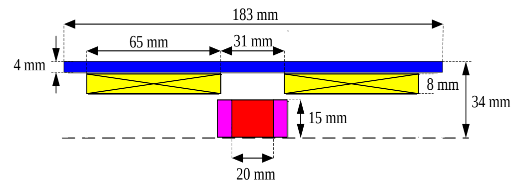

Figure 9: Full specification of chosen linear actuator.

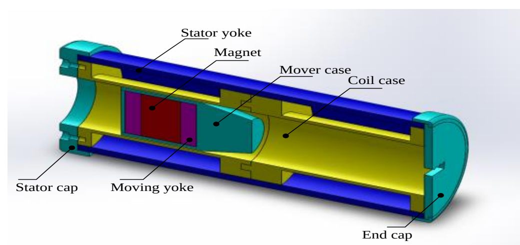

Figure 10: Cross-sectional view of linear actuator.

VI. CONCLUSION

As for the conclusion, slot-less linear actuator for food processing industries had been designed. It can help to minimize the usage of human energy and easy to handle. This paper is mainly focused on the analyzing the coil sizing of slot-less stator. Even though slot-type stator can produce higher thrust compared to slot-less, slot-less stator is more suitable to be used for this type of application that require compression. Minimum targeted thrust produce is 40 N and the maximum operating displacement is 70 mm. Thus, the best model of slot-less linear actuator chosen is the design of coils with the height of 8 mm and the gap between the coils is 31 mm. The current applied is 6 A as it fulfills the design specifications and expected thrust characteristic.

ACKNOWLEDGMENT

The authors would like to thank Ministry of Education & Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grant PJP/2015/FKE(5A)/S014203 & FRGS/1/2015/TK04/FKE/02/F00260.

REFERENCES

[1] B. U. Ravindra, Robert Nielssen, J. E. Brennvall. 2007. Force Analysis in Design of High Power Linear Permanent Magnet Actuator with Gas Spring in Drilling Application. Electric Machines and Drives Conference, pp. 285-288.

[2] U.A Bakshi, A.P Godse. 2009. Fleming's Right Hand Rule on Basic Electrical and Electronic Engineering, 1st edition, R.K University Publishing.

[3] R.N Firdaus. 2009. Development of Slotless Linear Oscillatory Actuator: M.Sc Thesis, Universiti Putra Malaysia.

[4] K. Bao-Quan, W. Hong-Xing, Li Li-Yi, Zhang Liang-Liang, Zhao Zhu, Cao Hai Chuan. 2009. The Thrust Characterictics Investigation of Double Side Plate Permanent Magnet Linear Synchronous Motor for EML. IEEE Transaction on Magnetic, pp. 501-505.

[5] Seok-Myeong Jang, Jan-Yong Choi, Han –Wook Cho, Sung-Ho Lee. 2005. Thrust Analysis and Measurement of Tubular Linear Actuator with Cylindrical Halbach Array. IEEE Transaction on Magnetic, pp 2028-2031.

[6] Xiofeng Zhou, Xiaoning Chen, Junyi Liu. 2007. The starting Thrust Simulation of a Tubular Linear Motor on the Base of Finite Element Analysis. IEEE Transaction Circuit and Systems, pp 909-912.

[7] Fumiya K., Katsuhiro H., M. Sakai, T. Yamada. 2013. Linear Oscillatory Actuator using New Magnetic Movement. International Conference of Mechatronics and Automation, pp. 431-436.

[8] M. Norhisam., Alias K., R. N. Firdaus, S. Mahmod, N. Mariun,J. Abdul Razak. 2006. Comparison on Thrust of Linear Oscillatory Actuators. 1st International Power and Energy Conference, pp. 470-475.

[9] John Avison. 1998. Relative Density of a Liquid in Physics for CXC 1st Edition. United Kingdom Publishing

[10] John Lawlor. 1991. Force in Auto Math Handbook. United States of America Publishing.

[11] Z. Fazlipour, R. Kianezhad, M.Razaz. 2015. Genetic Algorithm Based Design Optimization of a Six Phase Induction Motor. IEEE Transaction Circuit and Systems, pp. 1007-1014.

[12] Seok-Myeong, Jang-Young Choi, You Dae-Joon, Han-Wook Cho. 2005. The Influence of Mechanical Spring on The Dynamic Performance of a Moving-Magnet Linear Actuators with Cylindrical Halbach Array. Industry Applications Conference, pp.2132-2139.

[13] H. Yasuaki, N. Tomoharu 2012. A Proposal of Small Linear Actuator for Small Entertainment Robots. IEEE Transaction Computer and Informatics, pp.130-135.