UNIVERSITI PUTRA MALAYSIA

ANALYSIS OF THRUST DENSITY CALCULATION FOR LINEAR DC ACTUATORS

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By

NOOR AZITA BT AWALUDIN

Thesis Submitted to the School of Graduate Studies, University Putra Malaysia, in Fullfilment of the Requirement for the Degree of Master of Science

July 2006

DEDICATED TO:
MY FAMILY AND HAMDAN

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fullfilment of the requirement for the degree of Master of Science

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By

NOOR AZITA BINTI AWALUDIN

July 2006

Chairman : Norhisam Misron, PhD

Faculty : Engineering

In recent years, researcher has developed many actuators with different configurations depending on application required. Linear actuator has become one of the most popular actuator used in industry especially in factory automation. Linear motor, which have a compact and simple structure are easy to control compare to rotational motor [1]. The advantages of linear actuator are small size, low power and high thrust. The thrust of linear motor can be applied on to the load without any mechanical loss as rotation motor. But then, the generation of thrust produced by linear actuators is barely being fully investigated. Therefore, problem arises in producing low cost machine but with higher thrust production.

A study was conducted with the objective to investigate thrust density characteristics in relation with dimension. Two designs were tested, that is Linear DC actuator using electromagnetic application and Linear DC actuator which using permanent magnet

application. The range of current supplied to wound coil is 1 A to 3 A, while permanent magnet produced magnetic flux directly.

Expressions on the thrust generation on both linear actuators were derived in relation with the dimension and size of the machine. Derivation was done based on a few assumptions that may constitute to the objectives of this study. For clarification purposes, experiment on both linear actuators was done depending on the physical condition. Through the experimental result, comparison can be made between theoretical and experimental result in order to find the thrust density characteristic of linear actuator.

Basically, the objective of this study is achieved when comparison that has been made for both type of linear actuator shows the largest error was only 20%. For future improvement, a few prototype of linear actuator with different configuration of closed loop path for the flux to flow can be made. This study only concentrated on the same closed loop path of flux flows with a few assumption have to be taken which are the temperature and type of material for yoke is neglected. It is important to take the a few assumptions in order to focus on the thrust density characteristics in relation with the dimension.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

ANALISA KE ATAS KETUMPATAN DAYA TUJAHAN YANG DIHASILKAN OLEH PENDIKIT LINAR

Oleh

NOOR AZITA BINTI AWALUDIN

Julai 2006

Pengerusi : Norhisam Misron, PhD

Fakulti : Kejuruteraan

Dalam beberapa tahun kebelakangan ini, ramai penyelidik telah mereka cipta pelbagai pendikit linar dengan bermacam konfigurasi. Pendikit arus terus telah menjadi semakin popular terutama dalam bidang perindustrian dan juga automasi. Motor linar yang mempunyai struktur yang padat dan ringkas adalah mudah untuk dikendalikan. Antara faedah motor linar ialah mempunyai saiz yang kecil, berkuasa rendah dan menghasilkan daya tujahan yang tinggi. Daya tujahan yang dihasilkan boleh digunakan secara langsung tanpa bantuan alat tambahan. Tetapi, kajian ke atas penghasilan daya tujahan berbanding dengan saiz fizikal adalah kurang diberi perhatian. Oleh itu, timbul masalah dimana penghasilan mesin yang murah tetapi boleh memberi daya tujahan yang tinggi.

Oleh itu, satu kajian telah dijalankan dengan objektif untuk mengkaji karektor ketumpatan daya tujahan. Dua rekabentuk telah diuji, iaitu Pendikit Arus Terus Linar yang menggunakan aplikasi elektromagnet dan juga Pendikit Arus Terus Linar yang

menggunakan aplikasi magnet kekal. Julat arus adalah dari 1 A hingga 3 A, manakala magnet kekal menjana arus magnet dengan sendirinya.

Formula untuk daya tujahan bagi kedua-dua prototaip telah diuraikan dengan saiz atau dimensi sesuatu mesin telah dilakukan. Formula tersebut dihuraikan bersama-sama dengan beberapa anggapan yang sesuai. Untuk tujuan mengesahkan ketepatan nilai yang telah dikira, eksperimen telah dijalankan ke atas kedua-dua prototaip. Melalui eksperimen tersebut, perbandingan diantara nilai teori dan nilai eksperimen telah dilakukan untuk menganalisis karektor daya tujahan yang telah dihasilkan.

Secara umumnya, objektif kajian ini telah dicapai apabila perbandingan yang dilakukan antara nilai teori dan eksperimen menunjukan ralat yang paling besar hanyalah sebanyak 20% sahaja. Untuk masa hadapan, kajian boleh dilakukan untuk konfigurasi laluan garis medan magnet yang tertutup yang berlainan. Untuk kajian ini, konfigurasi yang serupa sahaja dilakukan. Ini bertujuan untuk memberi lebih fokus kepada daya tujahan yang dihasilkan berbanding faktor luar sebagai contoh; tahap kepanasan dan juga jenis bahan yang digunakan untuk membina teras.

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I certify that an Examination Committee met 11 July 2006 to conduct the final examination of Noor Azita Awaludin on her Master of Science thesis entitled "Analysis of Thrust Density for Linear DC Actuators" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master Science. The members of the Supervisory Committee are as follows:

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Date: 14 DECEMBER 2006

DECLARATION

I hereby declare that the thesis based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

NOOR AZITA BT AWALUDIN

Date: 17 NOVEMBER 2006

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CHAPTER 1

INTRODUCTION

Nowadays, linear motor become one of the most demanding machine in industry especially automation and factories. The demand of linear motor become increasing since the advantages that could benefits industry mainly in production cost. The design optimization of magnetic systems has been an important issue [1,2]. Among various components of magnetic systems, coil is the component that investigation is concerned [3]. Studies on linear motors and actuator have been well established by previous researcher in order to improve the quality and performance of production in industries involved. Among the advantages that can be provided by linear motor is small and easy to operate besides its ability to give the amount of power required. Usually, the structure of linear motors and linear actuators is simple and easy to understand. Although a few studies have been made on linear actuators, none of them has considered the thrust generation with relation to the dimension or the size of the machines. Therefore, this study is done on the main basis of the thrust generation to the dimension of the machine. In order for future development, the size of the machine can be reduced but producing a higher thrust density. This will give more advantages for industries in term of cost of production. Fig. 1.1 shows the flowchart of this study.

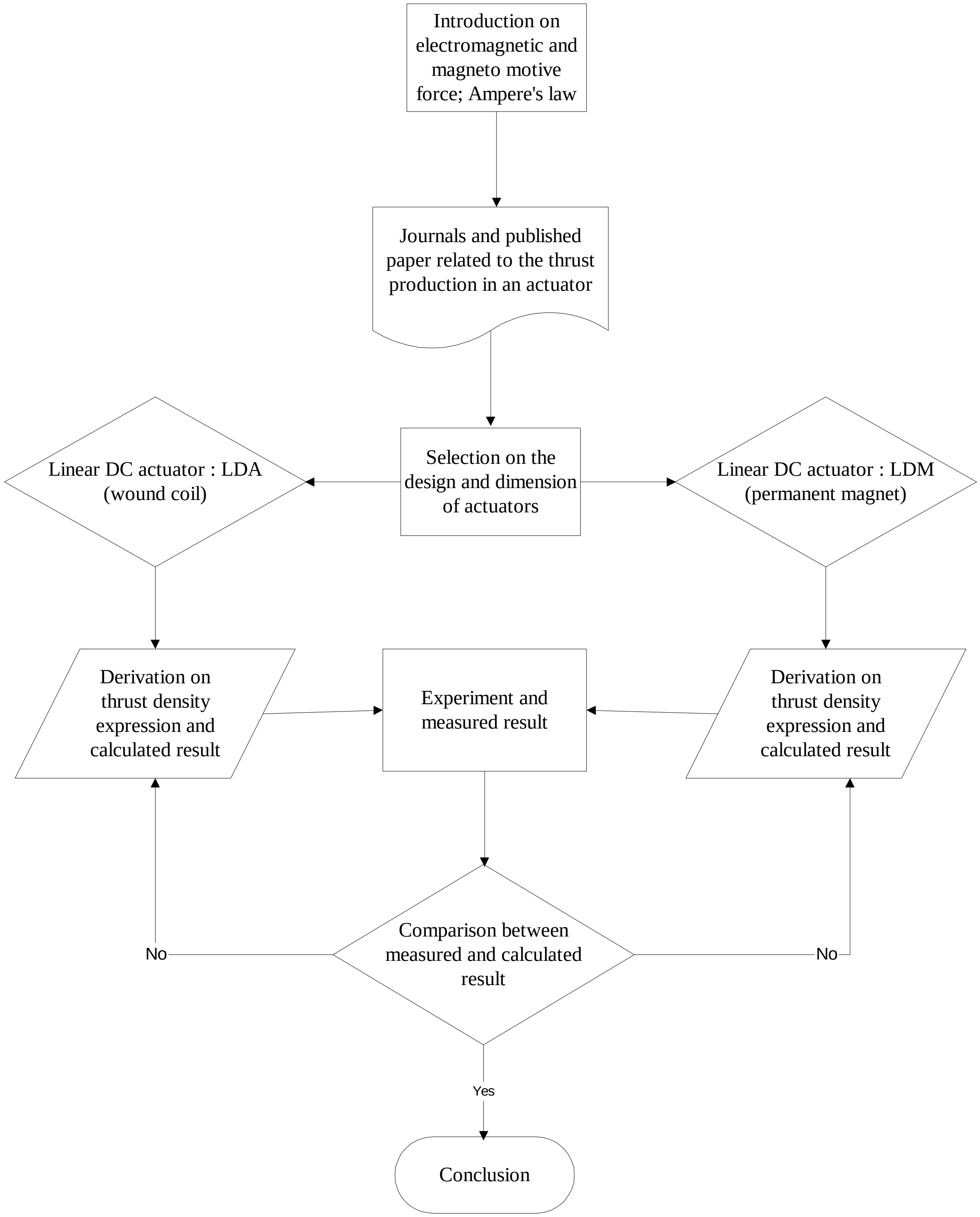

Figure. 1.1: Flowchart for general procedure done on study of Analysis of Thrust Density on Linear DC Actuator

Basically, linear actuator consists of wound coil supplied with current which act as stator and also permanent magnet itself. It does not need any auxiliary parts to operate such as gears or oscillating equipments. Linear actuator is an electromechanical devices which produce unidirectional or bidirectional short-stroke (less than a few meters) motion. Linear motions refer to a straight line motion [4].

Basically in linear actuator, its principle is based on the electromagnetic field theory, Maxwell's equations and Ampere's law. Naturally, these equations govern the electromagnetic phenomena in energy conversion devices [5]. Conventionally, when a conductor of length l carries a current I in a direction perpendicular to a magnetic field of flux density B, the conductor experience a force F perpendicular to both the direction of current flow and the magnetic field. This force is given by [5]

$$\boldsymbol{F} = \boldsymbol{IBl}$$

for a single wound conductor. In case of a linear motor, the magnitude of force produced is given by [5]

$$\boldsymbol{F} = \boldsymbol{NIBl}$$

where $\boldsymbol{N}$ is the number of turns of the conductor.

These basic equations of force or refer as thrust from now onwards, can be converged to a new formula with a few assumptions. Generally the computation of the total force is a natural extension of the local force calculation [6]. The main assumptions that have been made are excluding the temperature rise in the motor and there is no power loss or known as an ideal condition. Therefore, the equations may lack from a few basic supporting factors that effected the calculation, but it is important for us to bear in mind that the main point of this study is to make a comparison between the thrust generated with the calculated thrust's value in relation with the dimension of the actuator.

In the first scenario of magnetic fields applications, linear actuator using the electromagnetic application is used. From now onwards it is known as Electromagnet Actuator only for reference purposes in this study. Basically, this actuator is become widely use in factory and office appliances such as coffee machine or sliding door. Its simple structure and easy to control are among the advantages that can be offered. Linear actuators also gives a low production cost with highest thrust produced besides the fact that thrust can be directly used without additional auxiliary devices such as gears. A high precision positioning system generally adopts a linear motor as an actuator [7]. Using the basic concepts of Ampere's law, the equation of thrust produced in relation with the dimension of the electromagnet actuator can be derived. The main assumption taken was that the amount of the flux flow from the yoke of electromagnet actuator to air gap is same as the amount of the flux flow from air gap to the yoke again as shown in Fig.1.2. Therefore the thrust expression for electromagnet actuator is derived in this study. This expression shown the relationship between the magnetic densities produced with the dimension of the electromagnet actuator.

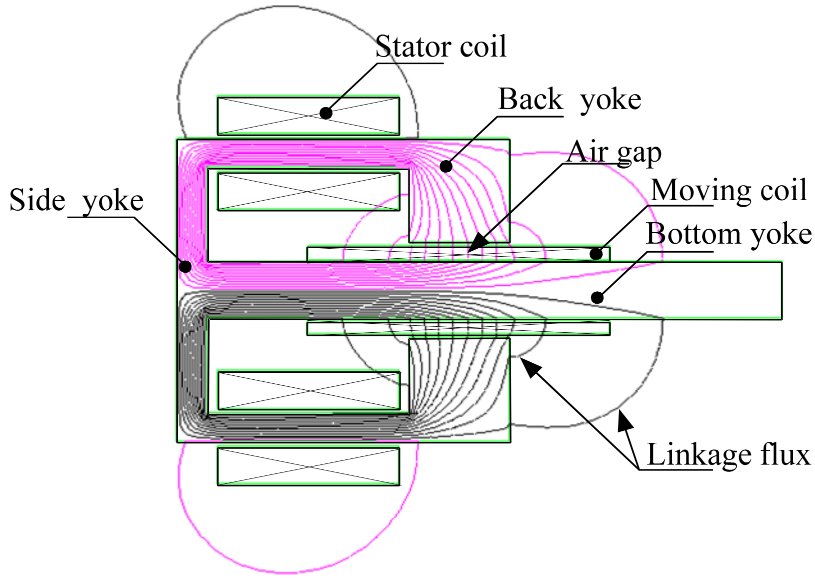

Figure. 1.2: Flux potential in electromagnet actuator

Using the equation derived, thrust calculation was derived by differentiation on the dimension of the electromagnet actuator. As a result, this calculated value can be compared to the experimental value, which is done by measuring the thrust produced in electromagnet actuator using the digital scale. Theoretically, the experiment value is expected to have nearly the same value with the calculation. The thrust characteristic for both experimental and calculation value is plotted and error analysis was made.

Mainly, for the second scenario of magnetic fields applications is using the permanent magnet in Linear DC actuator instead of wound coil supplied by current to act as stator as shown in Fig. 1.3. For reference purposes in this study, the actuator now and onwards is referred as permanent magnet actuator. The permanent magnets have been extensively used to replace the excitation winding in synchronous machines with the advantages of simple rotor design without field windings, slip rings and exciter generator, avoiding heat dissipation in the rotor and providing higher overall efficiency [8]. As known for the last few decades, the energy density of permanent magnets becomes improved with development of new materials. Basically, when using the permanent magnet, the most important thing to consider is the properties of the permanent magnet. The properties of the permanent magnet can be seen from the relationship between the flux density or magnetic density, B, and the magnetizing field strength, H, may be represented by the hysteresis loop. Besides the hysteresis loop, the permeance coefficient, p, also an important factor for applications of permanent magnet. The size of the Linear DC motor (permanent magnet actuator) is the main consideration in order to have small permanent magnet actuator but produced high thrust. As a result, through these factors, derivation on the thrust expression for permanent magnet in relation with the volume of permanent magnet actuator can be made. The thrust expression is derived. For permanent magnet actuator, the characteristic of thrust density is studied through the thrust and the volume of permanent magnet actuator. A few graphs was plotted in order to clarify the measurement value with calculated value of thrust. Dimension of permanent magnet actuator becomes the main parameter where the thrust density is related to the dimension of permanent magnet actuator, which means that the thrust generated in permanent magnet actuator can be calculated given the size of the motor.

Conclusion on both motor was made depending on the analysis of thrust characteristics and thrust density characteristics of respective linear dc actuators. Mainly, the objectives of this study is achieved where the relationship between the size of motor and the thrust generated become the main priority.

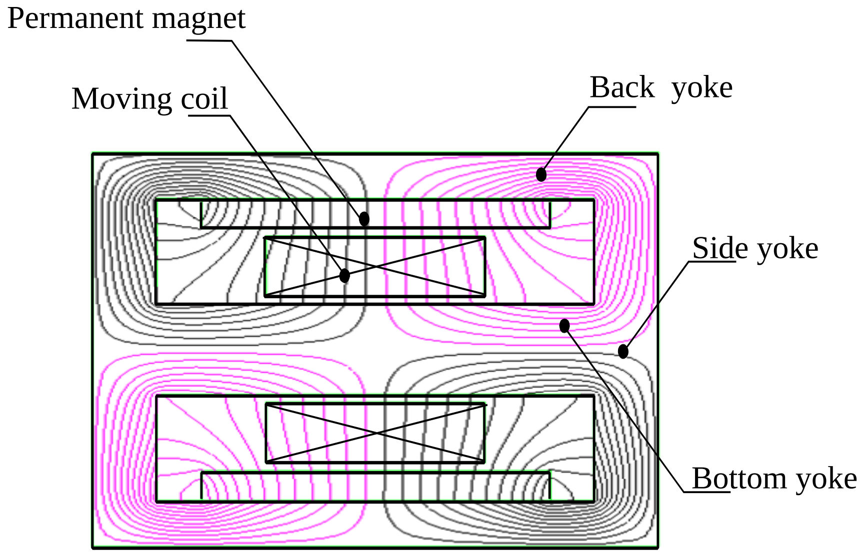

Figure 1.3: Flux potential in permanent magnet actuator

Methodologically, the analysis was done by conventional experiment and also through Finite Element Method (FEM). Nowadays, advanced research studies commonly employ standard FEM software packages for 3-D electromagnetic analysis and design [9]. FEM was used in order to see the magnetic density contribution through out both motors. The FEM is different in that an approximation of the solution itself is sought over a specified domain: that of a finite size, geometrical volume called a finite element. This approximation is then introduced in the field equation or an equivalent form of the field equations.

For modeling using FEM, the model of the designed actuator has to be drawn using software known as Microcal Origin. This modeling will be referred in creating three kind of file which are the bod, blk and mesh file. These file consists of information on the modeling structure in terms of numbers and coordinates. Then, element calculation is done by using software known as V mesh. It composes those three files within fra file. It calculates the element in the modeling structure. Then, fra file will be converted to mesh file using another software known as Cygwin. This software will show the element in the model in 2D. For magnetic analysis, a confiq file needs to be prepared. This file is a reference for femaph.exe for calculation. The confiq file consists of certain value of parameter that relates femaph.exe about the material of each block structure and even the magnetic properties. This parameter can be change for each different simulation. If magnetic analysis is successful, the results can be shown directly on the designed model as shown in Fig 1.2 and 1.3. It shows the flux potential in the motor which represented by different color of lines. This differences show two kinds of magnetic potentials which is North (N) and South (S). It is important to analyze the magnetic flux distribution in order to see the flux flow according to theoretical assumption. As a result, a strong expression derived based from the analysis done using FEM.

Both prototype of electromagnet actuator and permanent magnet actuator was built and used to measure the thrust density generated in every case. The size and dimension of prototype was set to be as small as it can be, so that the impact of thrust generated in the prototype can be seen. Referring to the volume, the thrust generated experimentally can be plotted and compared to the calculated value of thrust and the error can be calculated.

For experimental analysis, the set-up of both electromagnet actuator and permanent magnet actuator is the same where the thrust generated was measured using the digital