Force Characterization of an Electromagnetic Linear Actuator

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I hereby declare that I have read through this report entitled "Force Characterization of an Electromagnetic Linear Actuator" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Mechatronic engineering.

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I declare that this report entitle "Force Characterization of an Electromagnetic Linear Actuator" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Electromagnetic actuators are nowadays used in a vast variety of applications that require high thrust, high accuracy and different working ranges. The increasing advancements in the usage of electromagnetic actuators rises the need for more and more improvements in electromagnetic actuators especially in term of output force and working range. The thesis present an extensive characterizing study of two novel electromagnetic actuators each with different construction and characteristics aiming to analyze the behavior and output characteristics of the two designs and how these characteristics are effected by parameters and size variations. The two actuators are Tubular Linear Reluctance Actuator and Tubular Linear Permanent magnet with Halbach array Actuator. Each one of the designs has its own working principle, the Tubular Linear Reluctance Actuator employs induction motor principle where no permanent magnet is used and the other employs the synchronous motor principle where the mover is built of permanent magnets with one of the latest successful improvement of electromagnetic actuators. The study covers the variation of three parameter for each actuator air gap, number of turns and size. A comparative section is also presented for the purpose of comparison. The study concentrated extensively on the two characteristics of both actuators which are output thrust force and working range as they are considered two main concerns of any actuator design. The simulation is used to show the differences between the two design in many design aspects such as force, displacement and effects of parameters variations .The applied simulation is performed using 3D finite-element Ansoft software which is cabable of showing the magnetic field distribution in the whole actuator and predicting the strength and length of the output stroke.

ABSTRAK

Penggerak elektromagnet yang kini digunakan dalam pelbagai besar aplikasi yang memerlukan teras yang tinggi, ketepatan yang tinggi dan julat kerja yang berbeza. Kemajuan peningkatan dalam penggunaan penggerak elektromagnet meningkat keperluan untuk lebih banyak penambahbaikan dalam penggerak elektromagnet terutama dari segi daya pengeluaran dan pelbagai kerja. Tesis membentangkan kajian mencirikan banyak dua penggerak elektromagnet novel masing-masing dengan pembinaan dan ciri-ciri yang bertujuan untuk menganalisis tingkah laku dan output ciri-ciri kedua-dua reka bentuk dan bagaimana ciri-ciri ini dilaksanakan dengan parameter dan variasi saiz yang berbeza. Kedua-dua penggerak adalah tiub Linear Keengganan aktuator dan tiub Linear magnet Kekal Halbach pelbagai aktuator. Setiap satu daripada reka bentuk yang mempunyai prinsip sendiri kerja, yang tiub Linear Keengganan aktuator menggunakan prinsip motor induksi di mana tidak ada magnet kekal digunakan dan satu lagi menggunakan prinsip motor segerak mana penggerak itu dibina daripada magnet kekal dengan satu peningkatan berjaya terkini penggerak elektromagnet. Kajian ini meliputi perubahan tiga parameter bagi setiap ruang udara penggerak, bilangan lilitan dan saiz. Sebahagian perbandingan juga dikemukakan untuk tujuan perbandingan. Kajian tertumpu meluas di kedua-dua ciri-ciri kedua-dua penggerak yang output daya tujah dan pelbagai kerja kerana mereka dianggap dua kebimbangan utama mana-mana reka bentuk penggerak. Simulasi ini digunakan untuk menunjukkan perbezaan di antara kedua-dua reka bentuk dalam aspek reka bentuk banyak seperti kekerasan, anjakan dan kesan parameter variasi .The digunakan simulasi dilakukan menggunakan unsur terhingga perisian Ansoft 3D yang cabable menunjukkan taburan medan magnet dalam seluruh penggerak dan meramalkan kekuatan dan panjang output stroke.The FEM hasil analisis dan keputusan output strok dibentangkan.

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CHAPTER 1

1 INTRODUCTION

1.1 Background

Constant technology advancements have made people's live convenient and comfortable, the effects of technologies that had arrived from little inventions and led to very major advances can be clearly noticed, transmission is a significant one of them. The evolution of transmission technology has a major contribution in current easy and convenient live .Transmission is seen almost in every sector of today's technologies ranging from primary and heavy industrial automation to advance electronics and aerospace actuation.

Electromagnetic actuators are of the most well-known types of linear transmissions work by converting electric and /or magnetic power to mechanical motion through magnetic field interactions. Electromagnetic actuators have lately became an area of interest to a huge number of researchers as they found it compact sector toward efficiency drive improvement ,energy saving and significant alternative for many other types of actuators such as piezoelectric and rotary to linear actuators. Electromagnetic actuators provide a various number of advantages over other types of actuators such as higher force, lower needed power and higher efficiency which are comprehensively detailed in chapter 2. In this thesis two linear electromagnetic actuators will be designed and characterized for the purpose of comparison between different novel topologies of designing linear electromagnetic actuators.

1.2 Motivation

The recent advancement of linear actuators and the increasing demand for energy and environment saving gave rise of intensive use of electromagnetic actuators especially the types of electromagnetic actuator which consist mostly from permanent magnets. Electromagnetic actuators are nowadays replacing many types of actuators and conventional actuation methods and its future potential is day to day increasing.

Linear electromagnetic actuators provide new actuation method used almost in all todays advanced technologies such as:

- Industrial automation.
- Automotive and aerospace actuation.
- Robots and medical tools.
- Transportation.

It's well known that two of the most critical problems facing the world today are global warming and high energy consumption. The usage of linear electromagnetic actuators could effectively contribute in reducing the large amount of emissions caused by transportation by implementing the new generations of automobile engines as it contributed in significant energy saving and mechanical wear in many applications. For example Levitated train, the usage of Levitated train introduced three to five times reduction of energy utilized by railroads trains and totally reduced the mechanical wear due to the employment of non-contact new technology.

The extensive use of electromagnetic actuators rises the need for the characteristics' optimization of the actuators. By optimizing the structure of the electromagnetic actuator, many characteristics of the electromagnetics actuator will be improved such as thrust force and working range. This led to a short conclusion that, more work is needed in order to improve the electromagnetic linear actuators. One such a work can contribute in the modern evolution of transmission technology.

1.3 Problem Statement

Throughout world's industries, it is been proven that electromagnetic actuator has overcome many disadvantages in other types of actuators such as weariness in Electro-mechanical actuators, high required voltage and short travel in Piezoelectric actuators and leakage, imprecise positioning in Hydraulic and Pneumatic actuators. However , electromagnetic actuator still suffer the problem of low to average force production and designing an actuator with high force, long stroke and more compact geometry is still challenging work in many applications which rises the need for more and more improvement efforts especially in term of output force and working range. Hence, a great deal of efforts in the last decade have been dedicated toward the improvement of this type of actuators. This thesis focuses on characterizing two Electromagnetic linear actuators each with different construction and arrangement of coils and magnets. The two designs are considered to improve the thrust and working range. The two designs are characterized and exclusively investigated in term of force and working range in which can be considered a contribution to the extensively increasing advancement of linear electromagnetic actuators.

1.4 Objectives

1. To characterize two novel designs of tubular electromagnetic actuator to produce highest possible thrust force and determine the possible ranges.
2. To analyze the two designs using Finite Element Method (FEM).
3. To compare and evaluate the two designs in term of output forces and working ranges.

1.5 Scopes

1. Design and characterize two types of tubular linear micro-electromagnetic actuator.
2. Analyze the thrust output force and the working range of the two designs using Finite Element Method (FEM).
3. Optimize the thrust output force and the working range of the two designs in term of geometric, size and coil-permanent magnet arrangement.

1.6 Project Limitations

Two design limitations of the project:

1. As the one of the best type of electromagnetic actuator used permanent magnet to generate its output thrust and with the high price of magnetic materials but the project is limited to use as less permanent magnet as possible. This limitation caused the project to choose only one of the actuators with permanent magnet while the other will use iron.
2. The project is limited to a working range of 100 mm as its maximum.

1.7 Outline of the Report

Chapter 1: Introduction-This chapter introduces an overview of the project including purpose, limitation, and motivation. A general information about the linear actuator and covered topics of the project are also presented.

Chapter 2: Literature review- This chapter summarize the most relevant concepts and evolution relating to linear actuators in general and electromagnetic linear actuators in particular. This includes magnetic interactions, optimization and output force calculations.

Chapter 3: Methodology- This chapter describes the methods and procedures employed to design the project represented in a flow chart, conceptual design, and structure of designs. This chapter include also working principles and simulation method of the two designs of the project. The proposed analysis set up is also presented.

Chapter 4: Results and Discussion - This chapter illustrates the two designs of the two actuator fully with their complete parameters and discusses obtained results of both designs. Also a short comparison between designs is presented.

Chapter 5: Conclusion and recommendation- This chapter describes the conclusion of the project provides some recommendations for future works.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

Linear motion or what can be called rectilinear motion is a motion which takes place in a straight line. Linear motion is the basic of all kinds of motions. There are simple and complex products employing linear motion. These products are used in many kinds of machinery which are used exclusively to produce other technologies as its considered a main major part in manufacturing machines such as CNCs.

An actuator is an energy converting device which take one or more power source to create mechanical work or motion. The motion could be either linear (straight line) or rotary (rotation about a fixed point) in accordance with the requirements of the needed machine. The criteria of which an actuator is evaluated are output force, stroke speed and length, mover mass and power density and so on.

2.2 Overview of Actuators

2.2.1 Classification of Actuators

As actuators are energy converting devices, it convert an input from one or more sources to an output mechanical linear motion in a way which can be controlled using different methods. This energy conversion can be accomplished through different method depending on different operation principles and applications. According to different operation principles, linear actuators can be classified into four major and many minor types [1]. The four major types are presented in table (2.1) below.

Table 2-1 : Classes of actuators

Class of Actuator	**Energy Transform**	**Application**
Electromagnetic	Electrical-Magnetic-Mechanical	Solenoid, Voice Coil
Electromechanical	Electrical-Mechanical	Linear Drive, MEMS Comb Drives
Piezoelectric	Electrical-Mechanical	Ceramic, Polymer
Smart Materials	Thermal-Mechanical	Shape Memory Alloy, Bimetallic

These different classes of actuator employ different methods and principles to create the output motion. Electromagnetic actuators ; the actuation is created due to the interaction of the magnetic field created between coils, permanent magnets or coil and permanent actuator depending on the way they are arranged in a closed magnetic circuits. Piezoelectric actuators use Piezoelectricity which is represented in the electric charges that accumulates in a specific solid materials such as crystals, specific ceramics and so on in response to applied mechanical stress. The mechanism of actuation or motion in the shape memory alloys is change in the induced temperature which produces a significant shear strain when the material temperature is above the transformation.

2.2.2 Characterization of Actuators

Different Linear actuator exhibit different performance in term of output force [2], working range, needed voltage and robustness. A brief characterization of these actuators are presented in table (2.2) below.

Table 2-2 : Characterization of linear actuators

	Electrostatic	**Thermal**	**piezoelectric**	**Electromagnetic**
Force	Low	high	high	high
Working range	Short	long	moderate	long
voltage	High	low	moderate	low
Robustness	Moderate	moderate	high	high

Based on table (2.2), electromagnetic actuators provide high force and long working range with high robustness.

2.3 Electromagnetic Actuators

2.3.1 Magnetic Fields Interactions

Electromagnetic actuators in general employ magnetic field interactions to create magnetic forces and mechanical motions. The magnetic field is generated either by electric coil or the permanent magnet. Magnetic fields represent the fundamental mechanism by which the energy is converted from one form to another in the electromagnetic actuators.

Basic principles describe how magnetic fields employed in actuators [3]:

1. A current-carrying wire produces a magnetic field in the area around it.
2. A current-carrying wire in the presence of a magnetic field has a force induced on it (Motor principle).
3. A moving wire in the presence of a magnetic field has a voltage induced in it. (Generator principle).

2.3.2 Principles of Linear Electromagnetic Actuators

Electromagnetic actuators employ the principle of using coils and magnets to convert electrical and/or magnetic energy to mechanical energy. This conversion is accomplished through converting voltage and to motion (force and displacement). The force which create the mechanical motion over a specific range, is a result of the interaction of the magnetic field generated either by current currying conductor or permanent magnets [4].

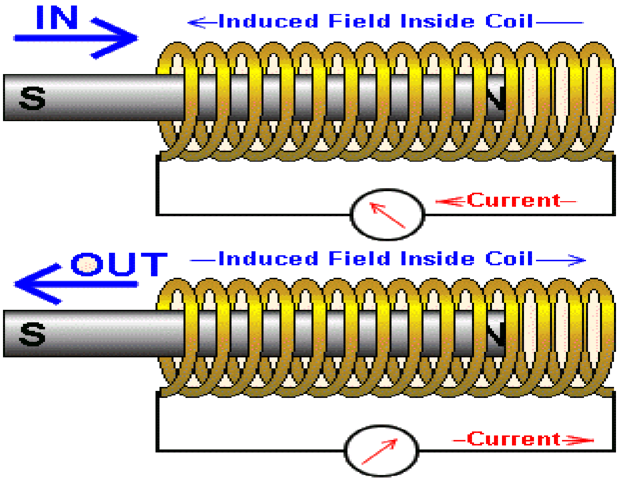

Figure 2.1: Basic principle of linear electromagnetic actuator [5]

As illustrated in figure 2.1 as the magnetic field of magnet traveling from north to south pole interact with the fields of the current currying conductor, force perpendicular to the fields is generated. The magnitude of the force depends in the density of the flux generated in the air gab.

$$F = ILB \quad (2.0)$$

Where F is the thrust output force, I is the current flowing in the conductor, L is the length of the coil and B is the flux density.

In order to determine the direction of the magnetic fields in a rounded set of coil (solenoid), the right hand rule is employed. The right hand figures are pointing with the direction of the current while the thumb is pointing to the North Pole where the field travels from S to N [6].An illustrative figure 2.2 is presented for clarity.

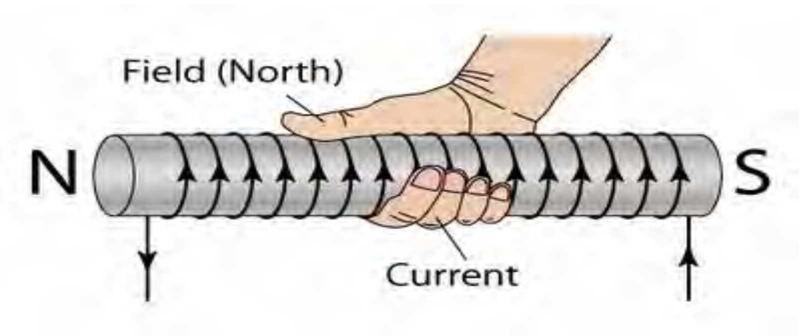

Figure 2.2: Right hand rule for determining the direction of the field [6]

2.4 Electromagnetic Linear Actuators

2.4.1 Classification of Electromagnetic Linear Actuators

There are two main components of any Electromagnetic linear actuator which are stator (Stationary part of the actuator) and mover (Moving part of the actuator). According to different arrangement and fabrication of these two component, electromagnetic linear actuator can be classified to two main categories which are flat and tubular geometry, each with its own performance characteristics .The configurations of the two categories is shown in figure 2.3 below.

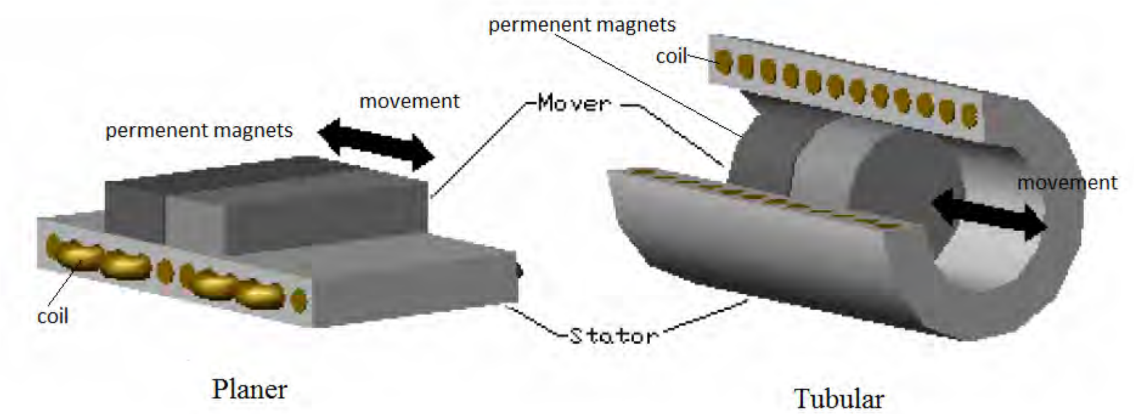

Figure 2.3: Two main categories of electromagnetic actuator [6]

A simple comparison of these two categories resulted in three conclusions:

- Tubular type mechanically is more rugged, which is a result of having all components inside piston like structure.
- Tubular type minimize if not eliminate stray magnetic field in the direction of travel.
- For the same sizes and weights of the actuators, the force density delivered by tubular actuator is greater than that by planer actuator [6].

2.4.2 Classification of Tubular Electromagnetic Linear Actuators

Tubular Electromagnetic linear actuators can be classified according to coil and magnet utilization and arrangement to three different topologies as depicted in figure (2.4) bellow moving coil [7] , moving iron[8] and moving magnet [9].

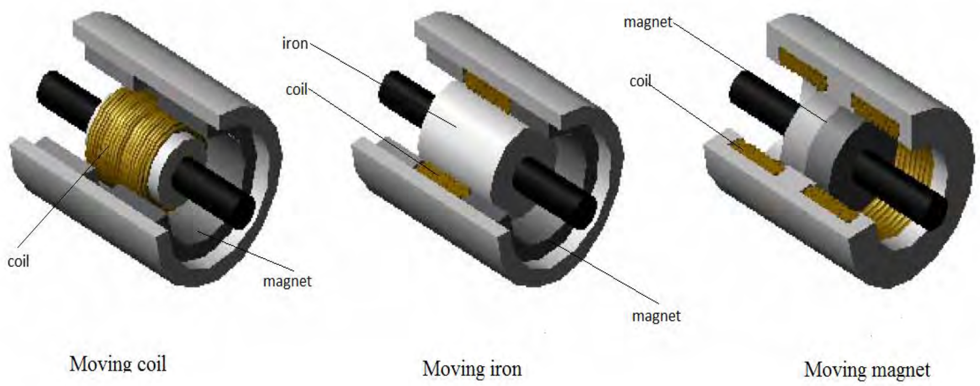

Figure 2.4 : Three topologies of linear actuators [9]

The performance characteristics of the three topologies of linear actuators can be summarized as:

Moving coil type which uses coil in the mover and PM (permanent magnet) in the stator. This type has small mover mass and high dynamics, but relative poor thermal dissipation, low reliability and large size. Moving iron exhibit high thrust force. But its large inertia can cause low dynamic performance resulting in less stability in the actuator. Moving magnet type have low mass mover and with the new improvements such as Halbach PM array, teeth optimization and so on, moving magnet can achieve higher thrust force and higher stability and accuracy.

Of the three different configuration of linear topologies, tubular permanent-magnet actuators provide the highest possible efficiency and high thrust force with excellent servo characteristics [10]. This led to the increment of the use tubular permanent-magnet actuators in many applications such as manufacturing [11], medical tools [12], transportation [13],