MODELLING AND SIMULATION OF A PERMANENT MAGNET DC LINEAR MOTOR

By

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FINAL REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
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(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

Ms Khairul Nisak Md Hasan
(*Project Supervisor*)

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June 2007

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohd Hafiz bin Ruslan

ABSTRACT

This report presents the project of modeling and simulation of a permanent magnet direct –current (DC) linear motor. The permanent magnet DC linear motor produces a linear motion. It produces motion in a straight line directly, without the use of a crank or any other mechanism for converting rotary motion to linear motion. The objectives of this project are to study on a permanent magnet DC linear motor, compare the efficiency between DC linear motor and DC rotary motor, design and simulate a model of permanent magnet DC linear motor with various loads and excitation conditions. In this project, after doing some study, a DC linear motor was compared with a DC rotary motor in terms of efficiency. A model of square-armature DC linear motor also was designed using MATLAB/Simulink and it was simulated with various loads and excitation conditions to observe the dynamic performances. The results obtained show that the DC rotary motor has higher efficiency compare to the DC linear motor. The dynamic performances of the permanent magnet DC linear motor such as velocity, output force, output power and efficiency are vary to each situations, where the higher armature excitation and lower load mass, the better the performances. After completing this project, the objectives were achieved and identified that a permanent magnet DC linear motor has great dynamic performances.

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CHAPTER 1

INTRODUCTION

1.1. Background of study

A linear motor produces motion in a straight line directly, without the use of a crank or any other mechanism for converting rotary motion to linear motion. The history of linear motor goes back as far as the last decade of the nineteenth century. These machines were practically forgotten for nearly half a century, but there has been a genuine revival of interest in them since the 1950s. Although linear motors dispense with the need for gears, belt, which are necessary to obtain linear motion from rotary motors, the latter are still preferred because of the wide range of speed and thrust that can be obtained with the help of gearing at an economic cost. However, it is predicted that more and more direct current (DC) linear motors will be used in linear drive applications in the future [1], [2].

Conventional dc linear motors are similar to rotating dc motors since they have an armature and a field system, but in the linear case the armature is stationary and the field is the moving part. The armature, in general, consists of a circular bar made of ferromagnetic material, with a single layer of enamelled copper wire closely wound on it. This layer of copper wire acts as both an armature winding and a commutator. The commutator is produced by removing the top surface of the wire insulation along which the brushes run. The field system is mounted inside the carriage, and it consists of a field winding and shaped yoke. The flux from a pole system crosses the air gap and interacts with the armature current to produce a force, and hence motion [3].

The permanent magnet DC linear motors are gaining increased attention due to the development in high-energy permanent magnets and advances in power electronics technology. Permanent magnet materials have a high coercive force; hence they are used to best advantage in DC motors, magnetic separators, and lifting devices where a high coercive force is required. Low power and low cost motors, which are mainly used for automobile accessories, employ these magnets extensively as segmental poles. Permanent magnet field motors offer several advantages over conventional, wound, field rotary and linear DC motors itself. Due to the absence of a field winding, the field system occupies less space, and the motor therefore becomes more compact and lighter. The possibility of motor breakdown due to failure of the field winding naturally reduces to zero, and the motors run at much cooler temperatures. The simplified assembly requirements of motors using permanent magnets reduce their cost and increases their reliability and efficiency [3], [4].

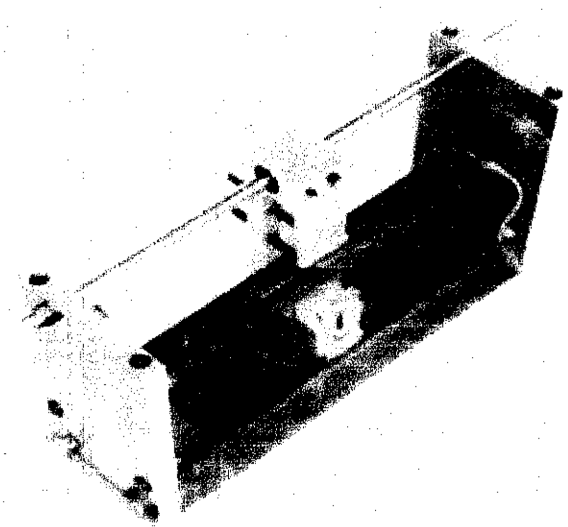

Figure 1: Example of permanent magnet DC linear motor [4].

1.2. Problem statement

1.2.1. Problem identification

The permanent magnet DC linear motors usually use high-energy permanent magnets materials. The high-energy permanent magnets such as neodymium-iron-boron (NdFeB) and samarium-cobalt (SmCo) are great desire in the design of electromechanical energy converters and give higher power density. But operation at higher current level increases the problems of saturation and armature reaction. This combination of saturation and armature reaction has undesirable effects in the permanent magnet DC linear motors. It leads to a nonlinear and asymmetric air-gap magnetic flux density, thus affect the dynamic characteristics of linear motors [4].

1.2.2. Significant of the project

The permanent magnet DC linear motors have dynamic characteristics such as velocity, output force, output power and efficiency. In this project, the model of square-armature DC linear motor was designed using MATLAB/Simulink based on the parameters taken from a book to obtain those dynamic characteristics [3]. The efficiency of the DC rotary motor also was plotted to compare with the DC linear motor. The parameters of the DC rotary motor were taken and modified from a note of 'Motor Calculations' [5].

1.3. Objective and scope of study

1.3.1. The relevancy of the project

The objectives of the project are:

i. To study on the permanent magnet DC linear motor.

ii. To compare the efficiency between DC linear motor and DC rotary motor.

iii. To develop and simulate a model of permanent magnet DC linear motor with various loads and excitation conditions and analyze its dynamic performance.

1.3.2. Feasibility of the project within the scope and time frame

The Final Year Project course has been given two semesters to complete and achieve its objective. To facilitate the project, study and literature reviews on the permanent magnet DC linear motor was conducted in the semester one. The study had covered the operation of principal, theory, types, and the development and researches on the permanent magnet DC linear motor. For the second semester, the project was completely finished by doing a comparison of performance between DC linear motor and DC rotary motor. A model of permanent magnet DC linear motor also had been designed and simulated using MATLAB/Simulink to obtain the dynamic characteristics of the motor.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1. Principle of operation of DC linear motor

A linear motor produces motion in a straight line directly, without the use of a crank or any other mechanism for converting rotary motion to linear motion. Conventional dc linear motors are similar to rotating dc motors since they have an armature and a field system, but in the linear case the armature is stationary and the field is the moving part. The armature, in general, consists of a circular bar made of ferromagnetic material, with a single layer of enamelled copper wire closely wound on it. This layer of copper wire acts as both an armature winding and a commutator. The commutator is produced by removing the top surface of the wire insulation along which the brushes run. The field system is mounted inside the carriage, and it consists of a field winding and shaped yoke. The flux from a pole system crosses the air gap and interacts with the armature current to produce a force, and hence motion [8].

2.2. Theory of DC linear motor

For a DC rotary motor, when a conductor of length l carries a current I in a direction perpendicular to a magnetic field of flux density B the conductor experiences a force F perpendicular to both the direction of current flow and the magnetic field. This force is given by

$$F = BIl \tag{1}$$

Considering the case of a linear motor, the force can be calculated in the following manner. This conventional theory is not rigorous, but it is included here since it was the first published analysis of DC linear motors. We can rewrite equation (1) as

$$F = \frac{\phi}{A_p}(I_a n_p)l_1 \tag{2}$$

Or $$F = \frac{\phi}{l_1 n_p / n}(I_a n_p)l_1 \tag{3}$$

Therefore, $$F = \phi n I_a \tag{4}$$

ϕ = the radial flux (in webers) entering the armature from the pole face

A_p = the pole face area (in m2)

I_a = the armature current (in amperes)

n_p = the number of conductors under a pole

l_1 = the length of a conductor under a pole (in metres)

n = the number of conductors per metre length of the armature

The magnetic circuit of the filed unit of a permanent magnet DC linear motor can be represented by the equation:

$$F(t) = \phi(t)\Re \tag{5}$$

where $F(t)$ is the magnetomotive force, $\phi(t)$ is the product of the flux density at the working point and the pole area, and $\Re$ is the reluctance of the circuit.

The armature voltage equation is given by:

$$e_a(t) = \phi(t)nv(t) + (R_a + L_a D)i_a(t) \tag{6}$$

where $\phi(t)nv(t)$ is the back e.m.f.

The electrical power which is converted to produce motion is:

$$P = e_b(t)i_a(t) \tag{7}$$

or

$$P = \phi(t)nv(t)i_a(t) \tag{8}$$

Therefore, the developed force is given by:

$$f_d(t) = \frac{P}{v(t)} = \phi(t)ni_a(t) \tag{9}$$

By balancing the developed force, $f_d(t)$, with the force absorbed by the motor due to the mass M, the friction F, and the mechanical load f, the dynamic equation can be written as:

$$f_d(t) = (MD + F)v(t) + f \tag{10}$$

2.3. Types of DC linear motors

Researchers in various countries, such as Japan, Germany, and the UK, have been working on DC linear motors for the last 25 years. The basic principles of these motors are similar in essence, but they differ widely in their construction and performance.

2.3.1. Configuration of various field units

Some of the factors involved in the design and analysis of two basic forms of DC linear motor were presented by Green and Paul. The first type has a multipolepiece field assembly, whereas the second configuration is based on a cylindrical field unit.

The former is most suitable when there is a wide range of displacement, and the latter may be used for more restricted ranges of displacement.

2.3.2. Brushless direct-current linear motor

While brushless DC motors most commonly provide rotary motion, there are several brushless DC motor configurations which also provide direct linear motion. These can be moving-magnet, moving-armature, or moving-coil motors. Although there are several differences between these types of motor, they all provide essentially the same basic linear motion.

2.3.3. Configurations of various stationary armatures

The length of a stationary armature depends on the travel length of the machine. The core material of the armature is mild steel. A glass type is usually wound on the armature to insulate the core material from the winding. In order to keep the air gap to a minimum, a single-turn winding is commonly used [8].

2.4. Permanent magnets

In the last few decades, as the energy density of permanent magnets has improved, there has been a large increase in the use of permanent-magnet materials in many nontraditional devices and also in energy-conversion systems such as motors and generators. A good permanent magnet should produce a high magnetic field with a low mass, and should be stable against the influences which would demagnetize it. The desirable properties of such magnets are typically stated in terms of the remanence and coercivity of the magnet materials. When a ferromagnetic material is magnetized in one direction, it will not relax back to zero magnetization when the imposed magnetizing field is removed. The amount of magnetization it retains at zero driving fields is called its remanence. It must be driven back to zero by a field in the opposite direction; the amount of reverse driving field required to demagnetize it is called its coercivity. If an alternating magnetic field is applied to the material, its magnetization will trace out a loop called a hysteresis loop. The lack of retraceability of the magnetization curve is the property called hysteresis and it is related to the existence of magnetic domains in the material. Once the magnetic domains are reoriented, it takes some energy to turn them back again. This property of ferrromagnetic materials is useful as a magnetic memory. Some compositions of ferromagnetic materials will retain an imposed magnetization indefinitely and are useful as permanent magnets. The alloys from which permanent magnets are made are often very difficult to handle metallurgically. They are mechanically hard and brittle. They may be cast and then ground into shape, or even ground to a powder and formed. From powders, they may be mixed with resin binders and then compressed and heat treated. Maximum anisotropy of the material is desirable, so to that end the materials are often heat treated in the presence of a strong magnetic field. The materials with high remanence and high coercivity from which permanent magnets are made are sometimes said to be "magnetically hard" to contrast them with the magnetically soft materials from which transformer cores and coils for electronics are made [9].

2.5. Recent researches and development of linear dc motor

Since the linear dc motor contributes more advantages, many research and developments have been done in order to improve the performance of the motor. By replacing ferrite-field magnet with the Neodymium-Iron-Boron (NdFeB) permanent magnets, it has been found that the static thrust generated by the NdFeB-field motors are two and a half times the static thrust generated by a similar sized ferrite-field motor. The output power and maximum power-to-weight ratio of the NdFeB having three times larger armature excitation compare to ferrite-field motor. The maximum efficiency of the NdFeB-field motor also being excited by three times larger current [2].

Two types of permanent magnet linear brushless motor which are a slotless-type permanent magnet and air core type permanent magnet could minimize the cogging force. Analysis of magnetic field in the air gap and coil area was done and the shape of the winding coil area has a significant effect on the thrust using an Equivalent Magnetizing Current (EMC) method. The EMC method has been developed to aid the magnetic field analysis [7].

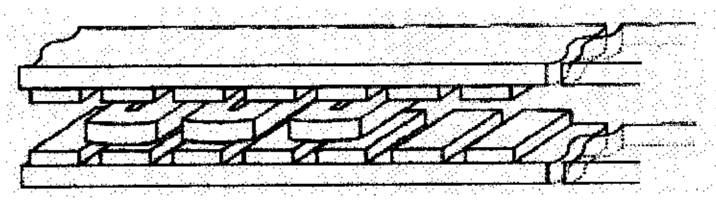

Figure 2: Structure of air core type PM linear brushless motor [7]

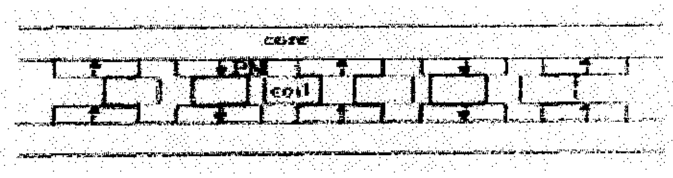

Figure 3: Cross section of air core type PM linear brushless motor [7]

The table below shows the summary of linear motor attributes and how each type of the motor compares to the others:

Table 1: Summary of linear motor attributes [6]

Attribute	Iron Core	Air core	Slotless
Cost	Low	High	Lowest
Attractive Force	Highest	None	Moderate
Cogging	Highest	None	Moderate
Force / Size	Best	Moderate	Good
Thermal Characteristics	Best	Worst	Good
Forcer Weight	Heaviest	Lightest	Moderate
Forcer Strength	Best	Worst	Good

Developments in high-energy permanent magnets have increased the attention of an energy-efficient in the permanent magnet DC linear motor. However, it still gives some unwanted phenomena to the motor which are armature reaction and saturation of the soft magnetic core of the permanent magnet DC linear motor. There are a few methods to design the motor such as analytical load line method, and two numerical approaches, simplified magnetic field and finite-element methods. To reduce the unwanted phenomena, two techniques can be applied like by using double armature motor (single permanent magnet) with sectional armature winding excitation and one more is by using heteropolar (double permanent magnet) motor with sectional armature winding excitation. The heteropolar design concept has proved to be the potentially best design alternative with respect to possible miniaturization at higher static thrust density [4].

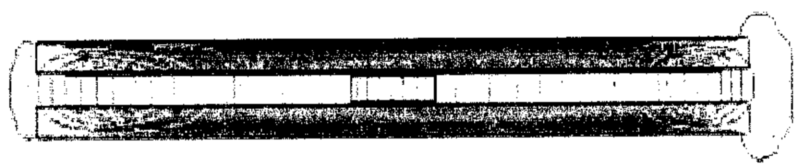

Figure 4: Axial field distribution of a double armature permanent magnet DC linear motor [4].

Figure 5: Axial field distribution of a heteropolar permanent magnet DC linear motor [4].

To simulate the control performance of the linear dc motor, a comparison was made between a three phase version and six phase version. Two different types of control methods are used to investigate the performance of the motor, namely constant damping force control and position and velocity feedback control. Results of operation were shown that six phase version having a much smoother operation [1].

2.6. Applications of linear motor

There are advantages in light and heavy industries in using linear rather than rotary motors for linear drives if the position and speed of these motors can be controlled precisely. Linear motors remove the necessity for gears, belts, etc., to transfer the rotary motion into linear motion. Thus they reduce the cost of the drive system, and also the space required for it. Direct current linear motors offer an impressive combination of precision, power, and speed. They can produce a thrust of up to 1 kN, accelerate loads to speeds in excess of 1.5 ms^{-1}, and then position the loads to submicrometre accuracies. This type of motor is, however, not easily adaptable to a variety of application demands, since gearing is impracticable. Therefore, in most linear-drive applications, requirements such as stroke-length, linear-velocity, acceleration and deceleration levels, need a motor which is uniquely designed for a particular application. In addition, the decision as to which type of moving magnet, moving armature or moving coil is best for a given application has to be made after the motion requirements are known. The major disadvantage of DC linear motors is their need for commutators and brushes, but this drawback is easily avoided by using electronics commutation. The main areas in which DC linear motors are applied are [8]:

1. materials handling in large and small industries
2. long-stroke positioning machines
3. positioning systems for robots
4. medical check-up equipment
5. detector head drives in industry
6. audio and lighting mixing decks
7. clean-room transportation
8. artificial hearts
9. textile machines
10. replacing hydraulic/pneumatic linear drives

CHAPTER 3
METHODOLOGY AND PROJECT WORK

3.1. Procedure identification

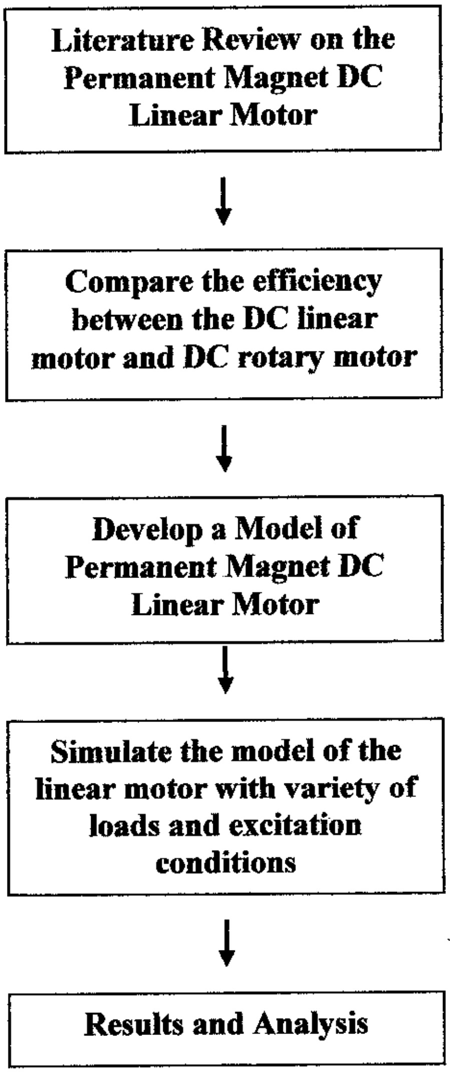

Figure 6: Project Methodology

3.1.1. Literature reviews on the permanent magnet DC linear motor

Literature reviews and study on the permanent magnet DC linear motor had been done on the first semester of this project. It covered the study of the principle of operation, theory, types, designing, development, and applications of the linear motor. All the literature reviews were done and taken from the books, articles, journals, and paper works of other researches.

3.1.2. Compare the efficiency between the DC linear motor and DC rotary motor

Comparison between DC linear motor and DC rotary motor was conducted to perceive the efficiency of each motor. The parameters of the DC linear motor were taken from the book entitled *Permanent-Magnet DC Linear Motors* by Amitava Basak whereas the parameters of the DC rotary motor were modified from the note of *Motor Calculations* by MicroMo, Inc. Miniature Drive Systems. Then, the graphs of the efficiency had been plotted using Microsoft Excel. Below are the tables of the parameters of DC linear motor and DC rotary motor:

Table 2: Output characteristics for DC linear motor [3]

Velocity (m/s)	**Power (Watts)**	**Efficiency (%)**
0.00	0.00	0.00
0.64	18.28	11.08
1.10	27.52	16.68
1.45	31.56	19.13
1.70	32.66	19.79
1.88	32.15	19.48
2.02	30.81	18.67
2.12	29.09	17.63

Table 3: Output characteristics for DC rotary motor [5]

Velocity (rad/sec)	Power (Watts)	Efficiency (%)
1032.72	0.729	75.74
839.51	1.186	64.91
646.29	1.369	50.72
453.08	1.280	35.92
356.47	1.133	28.35
259.87	0.918	20.73
163.26	0.634	13.05
66.65	0.282	5.34

3.1.3. Develop a model of permanent magnet DC linear motor

A model of permanent magnet DC linear motor was designed using MATLAB/Simulink. The model is the block diagram of the transfer function of a DC linear motor with a square armature. The transfer function was calculated and built by employing the equations of armature voltage and developed forces for the permanent-magnet field direct-current linear motors. Below is the table of the parameters of DC linear motor with square armature for various loads and excitation conditions and also the block diagram of its transfer function.

By using these equations, the parameters for the motor were obtained:

$$f = m_1 g$$

$$F_{eff} = \frac{KI_a - f}{v_0}$$

$$F = F_{eff} - \frac{K^2}{R_a + j\omega L_a}$$

$$\tau_m = \frac{M}{F_{eff}}$$

$$v(t) = \frac{KI_a - f}{F_{eff}}\left(1 - e^{-t/\tau_m}\right)$$

Table 4: Parameters for DC linear motor with square armature [3]

m_l (kg)	Ia (A)	M (kg)	K (Wbm^{-1})	v_0 (ms^{-1})	f (N)	F_{eff} (Nsm^{-1})	F (Nsm^{-1})	τ_m (s)
0.25	20	8.55	0.82	0.9	2.45	15.50	14.48	0.55
0.50	30	8.80	0.82	1.7	4.90	11.58	10.56	0.76
0.50	40	8.80	0.82	2.1	4.90	13.18	12.01	0.70
0.75	40	9.05	0.82	2.0	7.30	12.90	11.95	0.71
0.75	50	9.05	0.82	2.4	7.30	14.04	13.02	0.65
1.00	50	9.83	0.82	2.1	9.81	14.90	13.89	0.66

Mass of motor, M = 8.3 kg

Armature resistance, Ra = 0.06 Ω

Armature inductance, La = 0.00191 H

m_l = mass of load

f = mechanical force

g = gravitational constant

K = gain

Ia = armature current

F_{eff} = effective frictional coefficient

v_o = steady state velocity

v(t) = output velocity

F = frictional coefficient

τ_m = motor's time constant

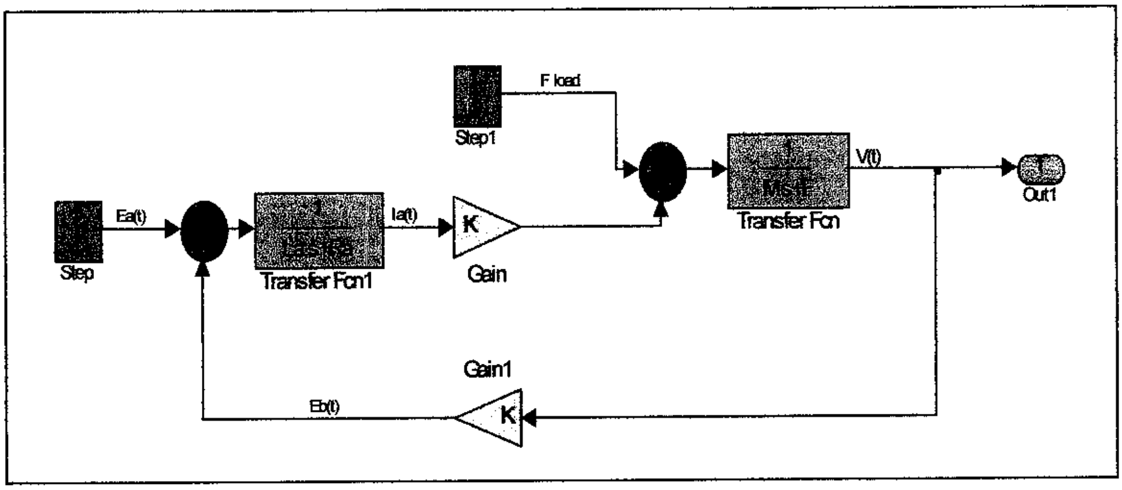

Figure 7: A block diagram of transfer function of a DC linear motor with square armature

3.1.4. Simulate the model of the linear motor with variety of loads and excitation conditions

After designing, the model had been simulated using MATLAB/Simulink to obtain the dynamic characteristics of the linear motor such velocity versus time, output force versus velocity, output power versus velocity, and efficiency versus velocity. All the simulations were carried out with different of loads and armature currents.

3.1.5. Results and Analysis

The results of the comparison between DC linear motor and DC rotary motor were plotted using Microsoft Excel. The graphs showed the efficiency of those motors. For the model of the linear motor with variety of loads and excitation conditions, the results were obtained from the simulation using MATLAB/Simulink and Microsoft Excel. The graphs showed the velocity, output force, output power, and efficiency of the motor for every condition.

3.2. Tools required

3.2.1. MATLAB/Simulink

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Simulink is a software package that enables the users to model, simulate, and analyze systems whose outputs change over time. Such systems are often referred to as dynamic systems. Simulink can be used to explore the behavior of a wide range of real-world [8].

CHAPTER 4
RESULTS AND DISCUSSION

4.1. Results

After taking some data, modeling, and simulation, some results have been obtained. The results displayed are the comparison of efficiency between DC linear motor and DC rotary motor and the dynamic characteristics of DC linear motor with various loads and excitation conditions in terms of velocity, output force, output power, and efficiency.

4.1.1. Comparison of efficiency between DC linear motor and DC rotary motor

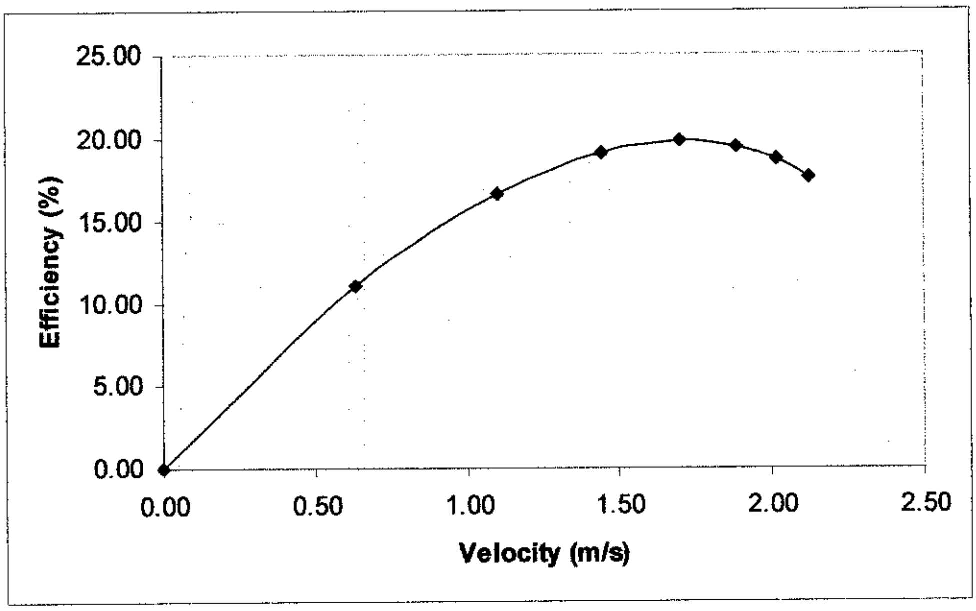

Figure 8: Efficiency versus velocity for Linear Motor

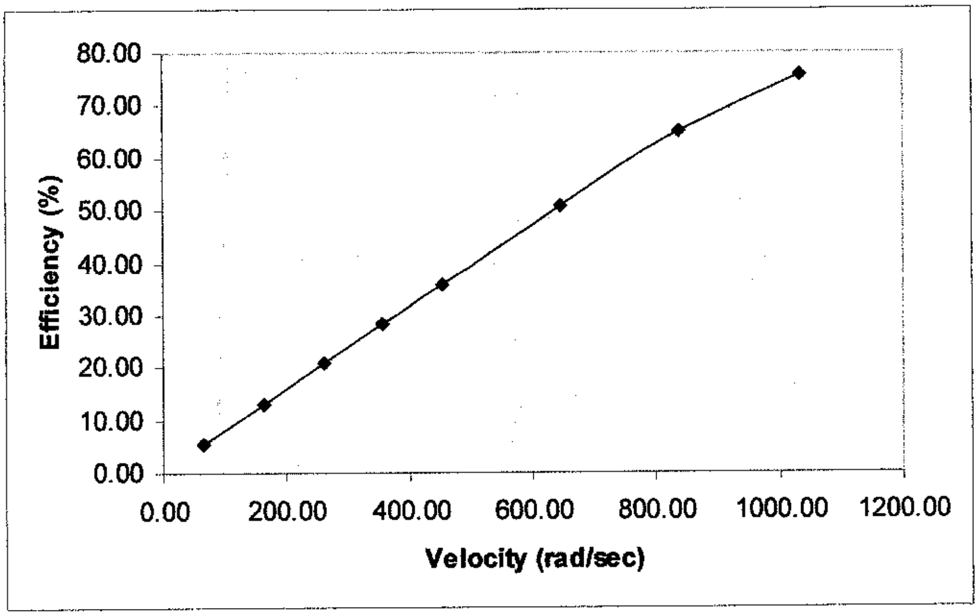

Figure 9: Efficiency versus velocity for Rotary Motor

4.1.2. Dynamic characteristics of DC linear motor with various loads and excitation conditions

4.1.2.1. Velocity

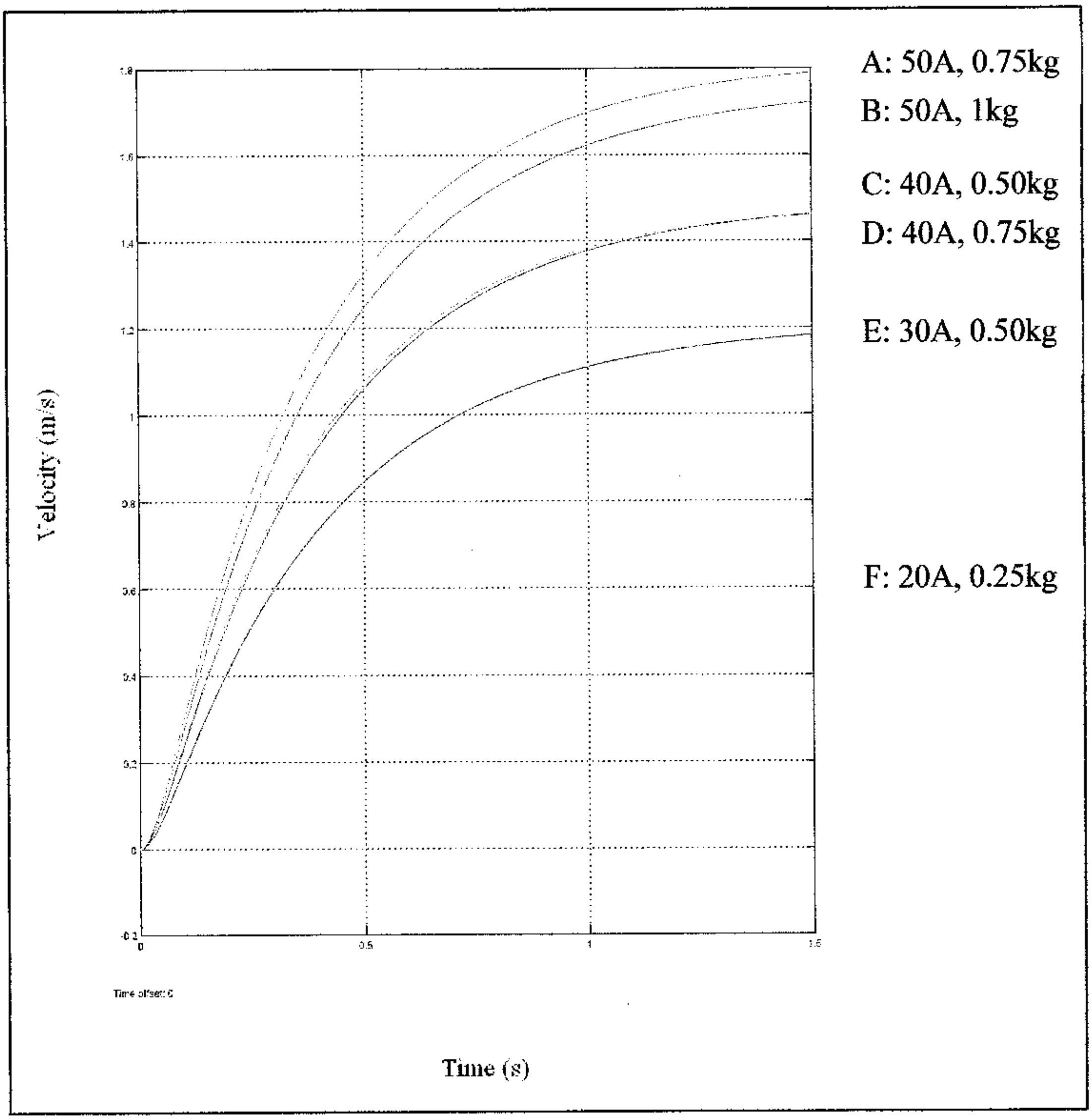

Figure 10: Velocity versus time characteristic

4.1.2.2. Output force

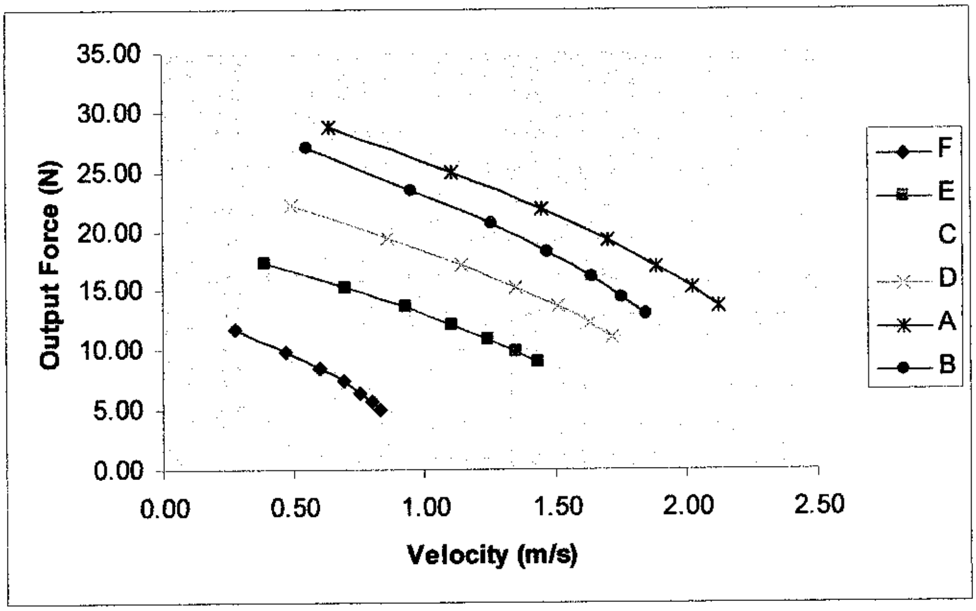

Figure 11: Output force versus velocity characteristic for (A) 50A, 0.75kg; (B) 50A, 1kg; (C) 40A, 0.50kg; (D) 40A, 0.75kg; (E) 30A, 0.50kg; (F) 20A, 0.25kg

4.1.2.3. Output power

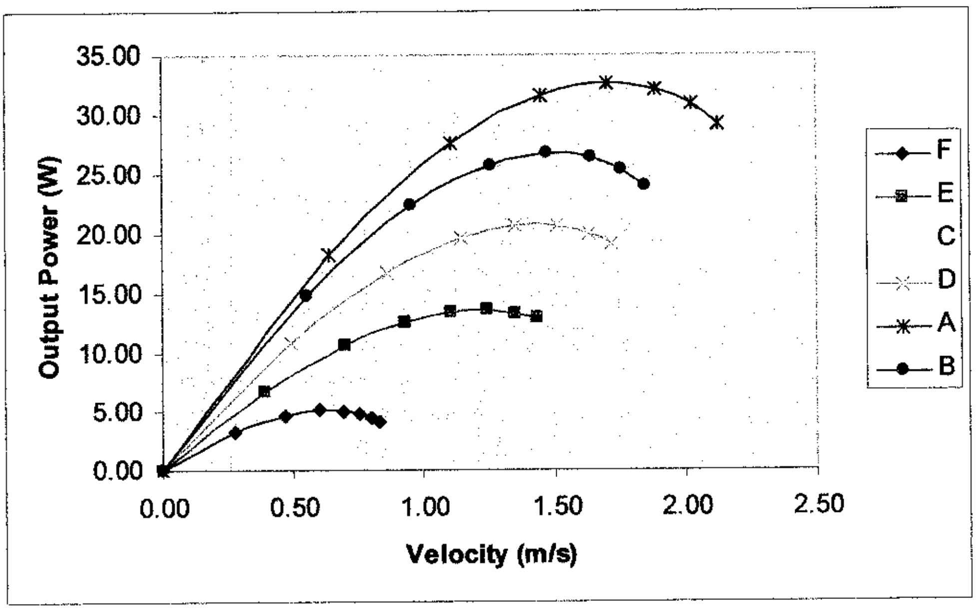

Figure 12: Output power versus velocity characteristic for (A) 50A, 0.75kg; (B) 50A, 1kg; (C) 40A, 0.50kg; (D) 40A, 0.75kg; (E) 30A, 0.50kg; (F) 20A, 0.25kg

4.1.2.4. Efficiency

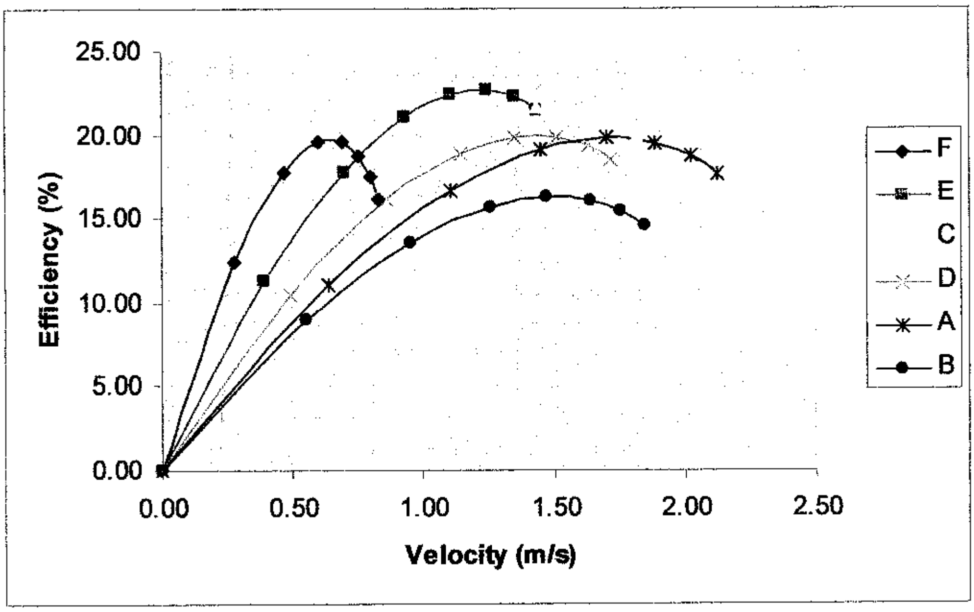

Figure 13: Efficiency versus velocity characteristic for (A) 50A, 0.75kg; (B) 50A, 1kg; (C) 40A, 0.50kg; (D) 40A, 0.75kg; (E) 30A, 0.50kg; (F) 20A, 0.25kg

4.2. Discussion

4.2.1. Comparison of efficiency between DC linear motor and DC rotary motor

From the Figure 8 and Figure 9, the graphs show that efficiency for DC rotary motor is higher than DC linear motor. As the theory, efficiency of the motor can be calculated by divide the mechanical power output with electrical power input. The lower efficiency of DC linear motor is almost entirely due to the fact that it operates with a large air gap, which results in a relatively high leakage flux, and also because of the friction from the support and guidance system. The magnetic circuit of a DC linear motor usually consists of a field source, the air gap, the back iron, and the armature core. The field source and the armature winding have different contributions to the flux distribution in the motor which depend on factors such as the armature current and the air gap length. The flux at any part of the motor is the vector sum of the flux produced by the field source and the flux produced by the armature current. The length of the air gap between the magnet poles and the armature should be uniformly maintained on either side of the armature, since unequal air gap lengths produce unbalanced force of attraction between the magnet poles and armature on either side. This results in a force component which is normal to the track length, and this affects the motion of the carriage and indirectly affects the efficiency.

The higher efficiency of DC rotary motor is due to high torque and high angular velocity (rotational distance per unit time). During normal operation, the spinning of the motor produces a voltage, known as the counter-EMF (CEMF) or back EMF, because it opposes the applied voltage on the motor. When current passes through the coil wound around a soft iron core the side of the positive pole is acted upon by an upwards force, while the other side is acted upon by a downward force. According to Fleming's left hand rule, the forces cause a turning effect on the coil making it rotate and to make the motor rotate in constant direction "direct current" commutators make the current reverse in direction every half a cycle thus causing the motor to rotate in the same direction. Since the CEMF is proportional to motor speed, when an electric motor is first started or is completely stalled, there is zero CEMF. Therefore the current through the armature is much higher. This high current will produce a strong magnetic field which will start the motor spinning with the high torque and angular velocity. The high torque multiplied by the high angular velocity produces a high rotational mechanical power; hence the higher efficiency is obtained.

4.2.2. Dynamic characteristics of linear motor with various loads and excitation conditions

4.2.2.1. Velocity

From the Figure 10, the graph shows that the velocity increases with time and it takes a long period before reaches a steady state. This happens at all loads and armature excitations. It takes a long period because of the friction generated by the motor itself and support and guidance system. In general, the armature is mechanically fixed to the base and therefore it forms the stationary part of motor, whereas the permanent magnet blocks are mounted inside the moving unit of the motor. Hence there is a movement of the field system relative to the armature. The powerful magnets housed in the moving unit produce a force of attraction between the poles and the armature on either side of the axis. The net force flattens the surface of the wheels after some usage; hence it increases the friction between the armature windings and the carriage. The motor with the lower excitations and higher load mass has lower steady state speeds and it also takes longer time to reach these speeds. It means high armature excitation but less load mass will give the motor a high velocity and short time to achieve the steady state velocity. It happens because the steady state velocity is proportional to the armature current but inversely proportional to the load mass. The higher the load mass, the more friction will be produced.

4.2.2.2. Output force

From the Figure 11, the graph shows that the output force decreases as velocity increases. The output force of the motor with higher excitations and lower load mass has higher output force compare to the motor with lower excitations and higher load mass. The output force produced is proportional to the current that passed through the armature. It is proved by the fundamental law of motor action that if a current is passed through a conductor which is perpendicular to a magnetic field, a mechanical force is exerted on the conductor in the direction perpendicular to both the armature current and the magnetic field. The output force of this motor can be determined from knowledge of the acceleration and the mass of the moving unit. As observed in Figure 10, the acceleration gradually decreases as the velocity increases. Therefore, the output force versus velocity characteristic should be expected to have the shape it has in Figure 11.

4.2.2.3. Output power

From the Figure 12, the graph shows that output power increases as velocity increase before it goes down after some points. This happens because of the output force generated is decreases as velocity increases, as illustrated in Figure 11. Output power for linear motion is the product of output force multiplied by velocity. Therefore, the graph for output power versus velocity characteristics looks like in the Figure 12. Like the output force, the motor with higher excitations and lower load mass has higher output power compare to the motor with lower excitations and higher load mass. The output power is proportional to the velocity which is related with the armature current and load mass. The more armature current passed through, the more velocity created and the higher the load mass, the more friction will be produced.

4.2.2.4. Efficiency

From the Figure 13, the graph shows the variation in the efficiency with velocity at different loads and excitations. Unlike the output force and output power characteristics, the efficiency versus velocity characteristic does not give a graph as higher excitation and lower load mass will achieve higher efficiency. This happens because the electrical power inputs of the motor are different for each condition (excitations and load mass). It can be determined from knowledge of the efficiency of the motor which is the mechanical power output divided by the electrical power input.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

By completing this project, the author had studied the permanent magnet DC linear motor. The operation of the linear motor is same like the rotary motor except in the linear case, the armature is a stationary part while the field system is a moving part. There are a few types of DC linear motor that use high-energy permanent magnet. The high coercive force of the permanent magnet materials has make them are used to best advantages in DC motors, magnetic separators, and lifting devices, and etc. The author also did a comparison of efficiency between DC linear motor and DC rotary motor. The DC linear motor produces much lower efficiency rather than the DC rotary motor, but it depends on its usage and applications. A model of permanent magnet DC linear motor with various loads and excitation conditions had been developed and it was simulated using MATLAB/Simulink. The dynamics characteristics of the linear motor with square armature such as velocity, output force, output power, and efficiency were obtained. The different loads and excitation conditions generate difference features of graph. As a permanent magnet DC linear motor has great dynamic performances, with the proper specifications it can be custom designed to provide servo systems with the fastest and most accurate prime mover that is currently available.

5.2. Recommendation

As this project was conducted based on the existing data, the author only can presented and obtained a few analyses of the linear motor performances. Therefore, it is recommended to other student who will do Final Year Project later on to do experimental measurements of this permanent magnet DC linear motor. By doing experimental measurements, more analyses could be obtained such as dynamic performances, static analysis, and the flux density distribution of the motor. It is also recommend that the student utilizes the xPC target box of MATLAB. The xPC Target is a possible solution for prototyping, testing, and deploying real-time systems using standard PC hardware. It is an environment that uses a target PC, separate from a host PC, for running real-time applications. To employ xPC Target and also other experimental measurements, it is strongly suggested that the university (UTP) provides a permanent magnet linear motor for the experimental purpose. Without the motor, the experiments could not be conducted.

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