



UNIVERSITI PUTRA MALAYSIA

DESIGN OF A LINEAR OSCILLATORY ACTUATOR FOR OIL PALM MECHANICAL CUTTER

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**DESIGN OF A LINEAR OSCILLATORY ACTUATOR FOR OIL PALM
MECHANICAL CUTTER**

By

FAIRUL AZHAR BIN ABDUL SHUKOR

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia
in Fulfilment of the Requirements for the Degree of Master of Science**

OCTOBER 2008



Dedication

**TO MY FAMILY, MAS HASLINDA MOHAMAD MY BELOVED WIFE AND
NURIN BATRISYIA FAIRUL AZHAR MY SWEET DAUGHTER**

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science

DESIGN OF A LINEAR OSCILLATORY ACTUATOR FOR OIL PALM MECHANICAL CUTTER

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JUNE 2008

Chairman: Dr. Eng. Norhisam Misron

Faculty: Engineering

At the early stage of their use, linear motors were particularly dedicated to transportation systems. Nowadays, linear motors are meant to replace a system using a rotating motor and a transmission to realize a linear movement. With linear motors, the performance of the system increased considerably since the mechanical limitations are removed. This leads to a better precision, a higher acceleration and a higher speed of the moving part. Therefore, direct drives with linear motors are increasingly used in industrial applications although these solutions normally lead to more investment costs.

In this research, the linear motor would be applied as part of an oil palm motorized cutter system. Due to its advantages especially in terms of producing linear motion the efficiency of the existing motorized cutter system is expected to improve. The existing system uses intermediate shaft and gears in order to convert rotary motion to linear motion for harvesting activity. However, the rotational transmissions become ineffective when it is used for palm trees higher than 5 meters. It is due to the fact

that intermediate shaft bends as the length increases. On top of that, it will increase the overall weight of the mechanical system as the length increases.

The new system of oil palm motorized cutter employs the linear oscillatory actuator (LOA) to replace the intermediate shaft and gear to produce linear motion. It eliminates the mechanical limit because there is no more intermediate shaft used in this system. The function of the intermediate shaft will be replaced by the copper wire in order to energize the LOA.

The LOA is an actuator in which a mover performs a reciprocating motion in a range of stroke as a result of being driven by a current having a sinusoidal or pulse wave form. The structure of LOA has been designed using FEM software by previous researcher. The drawback of the previous model is the lack of force to perform harvesting activity. Therefore in this research, the LOA design has been optimized to achieve high thrust of LOA. The method used in this design optimization is Permeance Analysis Method (PAM).

The design optimization is done by varying the size of permanent magnets and coils. In this design, it is ensured that the magnetic density saturation does not occur because, if it does, the thrust of the LOA will not increase even though the input current is increased. The constrain in this research is to develop the LOA within its limited overall weight. It is to make sure the LOA is mobile to the users. As a result, not only the high starter thrust of LOA about 200 N has been developed, but it is also light in weight which 2.0 kg and small in size which is $3.14 \times 10^{-4} \text{ m}^3$ in volume.

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

**REKABENTUK AKTUATOR ULANG ALIK LINEAR UNTUK PEMOTONG
BERMOTOR KELAPA SAWIT**

Oleh

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Pada awal penemuannya, motor linear banyak digunakan dalam sistem pengangkutan. Kebelakangan ini, motor linear dicipta bagi menggantikan sistem yang menggunakan motor putar dan pengubah untuk menghasilkan gerakan linear. Dengan menggunakan motor linear, prestasi sistem akan meningkat oleh kerana has mekanikal telah dihapuskan. Ini membawa kepada ketepatan, pecutan dan halaju bahagian bergerak yang lebih tinggi. Oleh itu, pemacu terus menggunakan motor linear semakin bertambah di dalam aplikasi industri walaupun teknik ini memerlukan kos pelaburan yang lebih tinggi.

Di dalam kajian ini, motor linear akan digunakan sebagai sebahagian daripada system pemotong mekanikal kelapa sawit. Oleh kerana kelebihanannya terutama di dalam menghasilkan pergerakan linear diharap agar dapat meninggikan kecekapan sistem pemotong mekanikal sedia ada. Sistem sedia ada menggunakan batang pengantara dan roda sawat untuk menukar gerakan putar kepada gerakan linear untuk kerja-kerja menuai. Walau bagaimana pun, pengubah putaran menjadi tidak efektif apabila ianya digunakan untuk pokok kelapa sawit yang melebihi ketinggian 5 meter.

Ini kerana batang pengantara akan bengkok apabila panjangnya bertambah. Selain daripada itu, berat keseluruhan sistem juga akan bertambah kerana sebab yang sama.

Sistem pemotong mekanikal kelapa sawit yang baru akan menggunakan aktuator pengayun linear (LOA) untuk menggantikan batang pengantara dan gear untuk menghasilkan gerakan linear. Ia akan menghapuskan had mekanikal kerana tiada lagi penggunaan batang pengantara digunakan di dalam sistem ini. Fungsi batang pengantara ini digantikan oleh wayar untuk menggerakkan LOA.

LOA adalah aktuator yang menghasilkan gerakan berulang di dalam lingkungan sesaran hasil daripada dipacu oleh arus di dalam gelombang sinusoidal atau gelombang segi empat. Struktur LOA telah direkabentuk oleh penyelidik yang terdahulu menggunakan perisian FEM. Kekurangan di dalam model yang terdahulu ialah tidak mempunyai nilai daya yang tidak mencukupi untuk menyempurnakan proses penuaian kelapa sawit. Sehubungan dengan itu, di dalam kajian ini, LOA tersebut akan direkabentuk semula dan dioptimumkan untuk mencapai nilai daya yang tinggi. Kaedah yang digunakan di dalam pengoptimuman LOA adalah 'Permeance Analysis Method' (PAM).

Pengoptimuman ini dijalankan dengan mengubah saiz magnet kekal dan koil. Di sepanjang proses rekabentuk ini, kesan ketepuan ketumpatan magnetik akan dipastikan tidak berlaku. Ini kerana, ketumpatan magnetik yang tepu akan menghalang nilai daya LOA dari terus meningkat walaupun bekalan arus terus dinaikkan. Halangan utama di dalam kajian ini adalah untuk membangunkan LOA yang ringan bagi memastikan ia mudah dibawa oleh para penanam kelapa sawit.

Hasilnya, LOA yang telah dibangun bukan hanya mempunyai nilai daya permulaan yang tinggi kira-kira 200 N, tetapi juga ringan dengan berat 2.0 kg dan kecil isipadunya iaitu kira-kira $3.14 \times 10^{-4} \text{ m}^3$.

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I certify that an examination committee met on October, 31 2008 to conduct the final examination of Fairul Azhar bin Abdul Shukor on his master of science thesis entitled “Design of Linear Oscillatory Actuator for Oil Palm Motorized Cutter” in accordance with University Putra Malaysia (higher degree) act 1980 and University 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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DECLARATION

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

FAIRUL AZHAR BIN ABDUL SHUKOR

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LIST OF ABBREVIATIONS

A_c	Cross sectional area of coil (m^2)
A_m	Cross sectional area of permanent magnet (m^2)
B_K	Magnetic flux density of permanent magnet at operating point (T)
B_r	Remanent magnetic flux density (T)
B_{sat}	Saturated magnetic flux density (T)
f	Frequency power supply (Hz)
F	Thrust (N)
G	Motor constant square density (N^2/Wm^3)
H_c	Coercive force (kA/m)
h_c	Height of coil (m)
h_t	Height of taper (m)
I	Current (A)
K_m	Motor constant (N/\sqrt{W})
k_s	Spring constant (kN/m)
L	Inductance (mH)
l_c	Length of average coils (m)
l_{cc}	Length between coils (m)
l_g	Length of gap (m)
l_{my}	Length of moving yoke (m)
l_{pm}	Length of one magnetic pole of permanent magnet (m)
l_t	Length of taper gap (m)
N	Number of coil turns
P	Permeance (H)
P_{in}	Input power (W)
P_T	Equivalent permeance (H)
R	Resistance (Ω)
r_2	Height of taper slope (m)
r_{by}	Thickness of back yoke (m)
r_{LOA}	Total radius of LOA (m)

r_m	Thickness of permanent magnet (m)
r_{PM}	Outer radius of permanent magnet (m)
r_s	Radius of shaft (m)
V	Volume of LOA (m ³)
W_c	Width of coil (m)
W_m	Magnetic energy (J)
x	LOA displacement (m)
Z	Impedance (Ω)
α	Angle of taper slope ($^\circ$)
δ	Height of air gap (m)
θ	Phase difference between voltage and current ($^\circ$)
μ_0	Vacuum permeability (4×10^{-7} H/m)
μ_r	Relativity permeability
ϕ_C	Magnetic flux of coil (Wb)
ϕ_{PM}	Magnetic flux of permanent magnet (Wb)
ρ_{Al}	Density of aluminium (2,800 kg/m ³)
ρ_{copper}	Density of copper (8,900 kg/m ³)
ρ_{iron}	Density of iron (7,800 kg/m ³)
ρ_{NdFeB}	Density of NdFeB permanent magnet (7,400 kg/m ³)
τ_e	Electrical time constant (s ⁻¹)
ω	Frequency (rad/s)

CHAPTER 1

INTRODUCTION

There are many linearly moving parts in mechanical systems, and in many cases these parts are driven by a rotary motor and rotary-to-linear converter such as ball screws, gears, belts, gears and etc. However, the rotary-to-linear-driving mechanism has some weak points, such as low acceleration performance, backlash, mechanical complexity and a low impact load capacity [1].

To encounter these disadvantages, linear motor was introduced. Operating without the rotary-to-linear transmissions parts, linear motor produces a linear motion that eliminates backlash and compliance. This reduces friction and wears and thus increases motor efficiency and precision, giving a higher acceleration and speed of the moving part [2]. Besides that, simple structure of linear motor offers high flexibility to the machine in terms of size and space [3].

Initially, the linear motors have been particularly dedicated to transportation systems. Nowadays, linear motors are used in various applications like automated manufacturing [4], embedded power generation [5,6], healthcare [7,8] and household appliances [9,10]. Since the introduction of high-speed cutting machines with linear direct drives in 1990s, linear motors have been widely known for their application in machine tools where high speed, high thrust, high reliability and long stroke are required [11-17].

The advantages attend by linear motors would be used in this research to develop an oil palm mechanical cutter. It would be used to replace the existing oil palm



mechanical cutter to eliminate the limitation of the mechanical system due to the use of rotary-to-linear transmissions parts such as intermediate shaft and gears to convert rotation motion produced by 2 stroke engine to linear motion in order to perform the cutting work [18]. The type of linear motor proposed for this application is linear oscillatory actuator (LOA). LOA is an actuator in which a mover performs a reciprocating motion in a range of stroke as a result of being driven by a current having a sinusoidal or pulse wave form [19]. To produce a high force density of LOA, permanent magnet type of LOA would be used for this application purpose [20].

The structure of LOA is inspired by Norhisam M. *et al*, [21], they designed the LOA using FEM software by optimizing the length of taper gap, l_t , and the height of taper gap, h_t . The purpose of optimizing these parameters is to produce high thrust of LOA at the same time has a low cogging and normal force.

The main contribution in this research is to optimize the thrust of LOA by using Permeance Analysis Method (PAM). The permeance equations for each displacement of LOA need to be derived in order to calculate the thrust of LOA. The dimension of LOA element such as size of permanent magnet, size of coil and length between coils will be varied to obtain optimized dimension to produce the highest possible thrust. The main constrain of this research is the total weight of LOA. This is to make sure that the oil palm mechanical cutter system is more practical.

1.1 PROBLEM STATEMENT

The motorized cutter which employs ‘rapid chopping method’ developed by MPOB was seen as a key breakthrough in the harvesting activity. However, this existing cutter is only limited to palm trees below 5 meters height. Palm trees higher than that will pose a problem to the cutter as it contributes to extra weight where the harvester could not afford to handle it. Furthermore, a longer pole would produce bending which consequently leads to the shaft to bend thus making the rotational transmission ineffective [18]. It is recognized that this ‘rapid chopping method’ has a great potential and therefore the demand to develop a longer reach (at least 12m) is necessary to solve the harvesting problem that the industry has been facing for years.

The heavy weight and limited reach of the existing mechanical cutter could be solved by adopting the Linear Oscillatory Actuator (LOA). The advantage of LOA is, that it is more efficient than the existing method since it is light in weight, it only uses wire instead of shaft transmission (existing cutter) to transmit the DC current to the motor, therefore the length and reach of the cutter can be further extended. In other words, bending of pole is no longer effect the system efficiency.

Thus, first prototype of slot type of LOA (called as LOA-01) for this application has been designed and developed in [21]. It has a maximum thrust about 150N at magneto motive force value (mmf) equal to 600A [21]. The LOA-01 has also been tested at MPOB laboratories. However, it shows that the LOA-01 is having inadequate thrust to perform the cutting. Therefore, the second prototype of LOA (called LOA-02) for the same application is designed and developed in this research. The LOA-02 will use the same structure as LOA-01 in [21]. The size of each element

in the LOA-02 will be optimized using Permeance Analysis Method to achieve high thrust value. The main constrain in the LOA-02 development is to maintain the overall size and weight as LOA-01. It is to make sure that the LOA-02 is mobile. The weight of LOA-02 was aimed below 2.0 kg.

1.2 OBJECTIVES

The aim of this research is to develop the Linear Oscillatory Actuator (LOA) to work as oil palm mechanical cutter. The LOA should have high thrust characteristics with light weight and small size. As a guide line along the design stage, the design target are listed below :-

1. Starter thrust : $> 200 \text{ N}$
2. Total LOA weight : $\leq 2.0 \text{ kg}$

1.3 SCOPE OF STUDY

In this research, focus is given on optimizing the structure of LOA-01 using Permeance Analysis Method so that it can achieve a high maximum thrust value. The optimization includes determining the size of magnet and coil as well as the length between coils and size of moving yoke. The optimization of the size of the LOA-01 in order to develop the LOA-02 is done by also considering the restricted total weight.

The optimization work started from derivations of permeance equation of LOA at every 1mm of it displacements. The thrust value is calculated using the calculated permeance value. The thrust value is verified by comparison between Permeance Analysis Method (PAM), Finite Element Method (FEM) and measurement values.

To design the LOA-02, the size of overall diameter is divided into five groups which have different values of total diameter. The size of permanent magnet in terms of its outer diameter is increased and at the same time decreasing the height of the coil to maintain the LOA-02 overall diameter. The thrust value is calculated for each group at certain combinations of permanent magnet and coil size. To avoid the saturation effect, the other element size for example high of taper slope, r_2 , length between coil, l_{cc} , and size of back yoke, r_{by} , are also considered. The model with the highest value of thrust for each group has been obtained. These models will be further evaluated using other parameter such total weight, motor constant and motor constant square density before the best model could be chosen as an oil palm mechanical cutter.

1.4 THESIS LAYOUT

The thesis consists of five chapters. Chapter One gives an overview and discusses the purpose of this study. The motivations of this study are addressed in the problem statement and the objectives of research also listed in this chapter. Chapter Two presents the literature reviews which have been carried out during the study. This chapter discusses the harvester tool used in oil palm industry from the previous time until it was mechanized. Basic operation and structure of oil palm motorized cutter introduced by MPOB and new system proposed to replace the existing system also has been explained. In this chapter, the linear oscillatory actuator (LOA) used to energize the new system of mechanical cutter has also been explained in terms of its basic structure and operation.

Chapter Three describes the methodology used in designing the LOA. This chapter starts with explanation approach in electrical machine design, differences, advantages

and disadvantages come with the difference approach. The approach chosen in this research has been stated. In this chapter, the equations used in the LOA development have been derived. The constrain faced in this research has also been explained in this chapter.

Chapter Four explains in details about the results obtained from calculation and measurement based on permeance analysis method explained in chapter three and the results from experiment of LOA characteristics. It includes the evaluation of LOA, thrust characteristics of LOA and frequency characteristics of LOA. Equipment used and its arrangement together with procedures have also been discussed. Chapter Five presents a conclusion of the overall study and recommendations for future work.