Doctoral Dissertation (Shinshu University)

STUDY ON LINEAR SYNCHRONOUS MOTOR DESIGN FOR OIL PALM CUTTER

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List of Abbreviations

Abbreviations

1PhSTLOA	Single phase slot type linear oscillatory actuator
FEM	Finite Element Method
LIM	Linear induction motor
LSM	Linear synchronous motor
LSTM	Linear stepper motor
PMCLSM	Permanent magnet cylindrical linear synchronous motor
PMLM	Permanent magnet linear motor
PAM	Permeance analysis method
SRCLSM	Switched reluctance cylindrical linear synchronous motor
SRLSM	Switched reluctance linear synchronous motor

Symbols

a	Copper wire cross sectional area	(m^2)
A_{DB}	Gain	(dB)
A	Gain	
$\overline{B}$	Magnetic flux density	(T)
δ	Air gap length	(m)
ΔF	Thrust ripple	(%)
Δx	Manufacturing tolerance	(μm)
$\|\Delta x\|$	Absolute manufacturing tolerance	(μm)
E	Young Modulus	(GPa)
$\overline{E}$	Electric field	(V)
ε_F	Thrust error	(%)
f	Frequency	(Hz)
f_{osc}	Oscillation frequency	(Hz)
F	Thrust	(N)
F_{ave}	Average thrust	(N)
F_C	Friction force	(N)
F_{fwd}	Forward direction force	(N)
F_{rev}	Reverse direction force	(N)
F_{cog}	Cogging force	(N)
$F_{annealing}$	Thrust of the SRCLSM with annealing mover	(N)
$F_{unannealing}$	Thrust of the SRCLSM with unannealing mover	(N)
F_D	Thrust difference	(%)
$F_{cutting}$	Cutting force	(N)
F_{max}	Maximum thrust	(N)

$F_{measured}$	Measured thrust	(N)
$F_{simulated}$	Simulated thrust	(N)
$F_{x=0}$	Starting thrust	(N)
θ_H	Phase difference of two phase	(^{O})
ξ	Space factor equal to 0.6	
G	Motor constant square density	(N^2/Wm^3)
$\overline{H}$	Magnetic field intensity	(kA/m)
h_c	Height of coil	(m)
h_{pm}	Height of permanent magnet	(m)
I	Current	(A)
I_p	Peak current	(A)
I_ϕ	Phase current	(A)
Re {I}	Real parts of current expression	(A)
Im {I}	Imaginary parts of current expression	(A)
$i(t)$	Function current in time domain	(A)
$\overline{J}$	Current density	(A/m^3)
k_f	Thrust constant	(N/A)
k_m	Motor constant	($N/\sqrt{W}$)
l	Copper wire length	(m)
l_y	Length of stator	(m)
L	Coil inductance	(H)
L_{max}	Maximum inductance	(H)
L_{min}	Minimum inductance	(H)
m	Mover's mass	(kg)
N	Coil turns	
P_{in}	Input power	(W)
P_T	Power consumption	(W)
ϕ	Phase different	(^{O})
ϕ_C	Copper wire diameter	(m)
r_{pm}	Radius of permanent magnet	(m)
r_s	Shaft radius	(m)
r_{total}	Total radius	(m)
R	Coil resistance	(Ω)
R_S	Standard resistance	(Ω)
R_{max}	Maximum resistance	(Ω)
R_{min}	Minimum resistance	(Ω)
$\rho_{material}$	Material density	(kg/m^3)
t_s	Slot width	(m)
t_w	Teeth width	(m)
t_y	Yoke thickness	(m)
THD_F	Total harmonic distortion of thrust	(%)

σ_t	Tensile Strength	(MPa)
σ_y	Yield Strength	(MPa)
τ_c	Coil pitch	(m)
τ_e	Electrical time constant	(s)
$\tau_{e,max}$	Maximum electrical time constant	(s)
$\tau_{e,min}$	Minimum electrical time constant	(s)
τ_m	Mechanical time constant	(s)
τ_p	Teeth pitch	(m)
τ_{pm}	Magnetic pole pitch	(m)
v_m	Mover speed	(m/s)
V	Volume	(m^3)
v	Poisson ratio	
$v(t)$	Function of voltage in time domain	(V)
v_{part}	Volume of linear motor part	(m^3)
V_{mot}	Motor volume	(m^3)
Re {V}	Real parts of voltage expression	(V)
Im {V} (V)	Imaginary parts of voltage expression	
W_{coil}, W_{pm} and W_{yoke}	Weight of the linear motor particular parts	(kg)
W_c	Coil width	(m)
W_{tot}	Total weight	(kg)
ω	Angular Frequency	(rad/s)
x	Displacement	(m)
x_T	Total displacement	(m)
$+x$	Most positive displacement	(m)
$-x$	Most negative displacement	(m)

Chapter 1: Introduction

Agricultural activity could be described as the science, art and business of cultivating soil, producing crops and raising livestock [1.1]. Even though agriculture activity is seen as uninteresting, low income and productivity of economic activity, but the contribution from this activity cannot be neglected especially in matters concerning food security. For example, in China, having only 7% of the world's total cultivated farmland, could support about 20% of the world's population's needs [1.2]. Moreover, agricultural sectors are also playing a role as a major economic contributor in several countries. In South Africa for instance, agricultural sectors provided 60% of employment opportunities and generated 27% of gross national product (GDP) in 2001 [1.3]. That same year, about 80% of Nepal's people were involved in agricultural economic activities yet contributed to about 40% of its GDP [1.4], [1.5]. For Nigeria, contribution of agricultural against its GDP has been shown increment pattern from about 51 % on 1970 to about 65 % on 2010 [1.6]. Even for USA, at New York State alone, agricultural contribute about USD 53,719 million to economic output with about 206,604 on employment contributions [1.7].

Oil palm is the world's most fruit crop in the agricultural sector. It is caused by its unparalleled productivity and most productive oil plant in the world. The oil palm or it scientific name known as Elaeis guineensis is a tree without branches but with many wide leaves on its top or called as tree crown. The fruits are compactly packed in bunches which are hidden in the leaf axils in crowns [1.8]. The oil palm could live up to 30 years and could reaches height of 15 meters with a stem diameter about 45 cm [1.9].

The palm oil could be found in numerous end products either in edible based and non-edible based product [1.10]. Figure 1.1 shows the product that could be derived from the palm oil [1.1], [1.10]. Despite of non-edible based product, the production of palm oil is most focus in edible product such as cooking oil and margarine [1.10]. Although ranked fourth in decades ago, awareness of the negative effects of Trans Fat on human health has caused palm oil becomes the most consumed vegetable oil in the world [1.8]. Conjunction with that, the production of palm oil is expected to increase 3.47%/ year to support this demand. It will be estimated, in 2015, palm oil is set to become the most produced oil with total production of 37.41 million tonnes, surpassing soya bean oil (1.10).

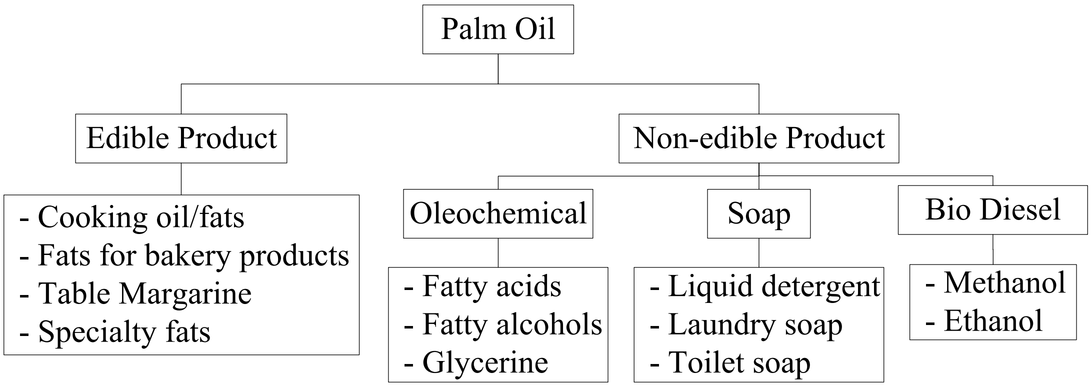

Figure 1.1 Type of end product of palm oil.

In order to support palm oil's demand, its productivity needs to be improved. There are several ways has been suggested to be implemented to increase the productivity of the agricultural product such as increase the labour productivity through improved service extension, reintroduction of the fertilizer, improved seed and enhance agricultural mechanization (1.11). Therefore, in this research, improvement of the oil palm productivity through mechanization is focused.

Agricultural mechanization could be defined as an economic application of engineering technology to enhance the effectiveness and productivity of human labour (1.12). The main objective of agricultural mechanization is reduce human drudgery, improve timeliness of operation, increase cultivation rate of an area of land and improve economy and standard of living of farmers through increased productivity (1.13).

Mechanization has proven to enhance the agricultural activities and ensure sustainable agricultural production (1.14). For example in the USA, farm mechanization allowed one farmer to feed from 5 people in 1880 to 80 people in 1982 (1.15). In India, farm mechanization started in the 1970s. It shows that land productivity has increased drastically since the introduction of farm mechanization as a mechanical power source in India from about 0.80 kg/ha to 1.45 kg/ha (1.16).

Agricultural mechanization also aims to reduce human energy along the cultivated activity. Nkakini *et al* (2006), has reported comparison of the energy used to produce the same amount of cassava both manually and machine assisted. Based on the result, machine assisted operations have 83 times lower energy consumption compared to the manual operation of the same quantity of product (1.17). On the other hand, in China, mechanization has become the latest economical source for the nation (1.2).

Agricultural mechanization has been put in place during processing raw material to final product, land preparation, weeding, harvesting, pest control, irrigation and drainage, transportation and storage. The process cycle of oil palm based product starts with cultivation and harvesting activity (1.18). Cultivation and harvesting involve seeding, fertilizing, weeding, cutting fronds and fruit bunches, collecting and transporting the fruit bunches to an industrial site for end product processing. Mechanization has considerable help to reduce the human effort to accomplish these activities. It also proven could improve the productivity of the palm oil production. For example, in weeding activities, through the mechanization has increased the ratio of labour to land hectare from 1 : 25 to 1 : 50. On the other hand, mechanization in fresh fruit bunch (FFB) collection has increased the earnings of the oil palm plantation company from about USD 4.96 per day to USD 14.52 per day (1.13). Current technology has made further activity along the oil palm cultivation has been mechanized. WIW. Ismail *et al.*, 2000 & 2009 report regarding the vision system for prediction of fruit ripening development. It helps the harvester to harvest only the ripe fruit for palm oil quality guaranteed. However, the result of actual implementation of this technology has yet to be discovered. MS. Deraman *et al.*, 2007 discussed about the roller-type oil palm loose fruit picker development. It eases the harvester to pick loose fruit compares to before the introductory of this tools, the loose fruit was by hand collected.

In this research, mechanization of oil palm FFB harvesting tools was discussed. In Malaysia, efforts to develop mechanize oil palm FFB harvesting tools was initiated by the Malaysian Palm Oil Board (MPOB). The MPOB has introduced a mechanical based cutter known as *Cantas*™ (1.22) - (1.24). The *Cantas*™ has demonstrated its capability to improve the oil palm FFB harvesting productivity through several fields testing sessions. It is found that, the *Cantas*™ could increase the oil palm FFB harvesting productivity more than twice compared to traditional technique. Despite of it merits, due to weight of the top side of the *Cantas*™ made it become less efficient to harvest oil palm FFB located more than 8 meters in height (1.25). At this height, the pole of *Cantas*™ starts to bends and made the mechanical system inside the *Cantas*™ stop working.

Due to the impressive performance of the *Cantas*™, urge a solution needs to be discovered to at least bring the same performance to the higher oil palm. Therefore, an electrical based cutter or called as E-Cutter was introduced (1.25) - (1.27). Through implementation of E-Cutter, the pole bending problem no longer disturb the function of harvesting tools by equipped this tool with flexible features.

1.1 Problem Statement

Development of *Cantas*™ by the MPOB is seen as a breakthrough to implementation of mechanization to oil palm FFB harvesting activity. Impressive performance has been shown by the *Cantas*™ through several field testing especially in term of cost and time performances. However, the operation of *Cantas*™ becomes less efficient at height of oil palm higher than 8 meters. At the height of the oil palm higher than 8 meters, the pole bending problem made the mechanical system of the *Cantas*™ was stopped and harvesting activity was unfeasible to accomplish.

The pole bending is caused by the weight of the top side of the *Cantas*™. Since this factor could not be neglected, more flexible tools are required (1.26), (1.27). Therefore, instead of mechanical based system employed in *Cantas*™, an electrical based harvesting tool called as E-Cutter has been proposed (1.25) - (1.27). The structure of E-Cutter will be similar as *Cantas*™. An electrical generation system consist of 1.3 hp petrol engine coupled with an electrical generator will be placed on the bottom part of the E-Cutter. At the top side of the E-Cutter, a linear motor attached with a sickle will be placed to perform cutting operation. By using electrical based instead of mechanical based system, the pole bending problem will be no longer influence the operation of the harvesting tool.

In this research, the linear motor for the E-Cutter has been designed. Several prototypes of the linear motor comprise a single phase with slot and slotless stator type structure topology has been designed previously (1.28) - (1.31). Despite of all the linear motors have been designed and developed, the slot stator type linear motor as described in [1.31] is considered as the best model for the E-Cutter so far. The structure of the slot type linear motor has been designed in order to maximise it thrust while maintaining its restricted weight. It has thrust at mover displacement, x of 0 mm, $F_{x=0}$ of 230 N and total weight, W_{tot} of 2.0 kg. The slot type of linear motor has been tested in laboratory before it could be confirmed to be implemented for E-Cutter actuator. Based on the testing result, it was confirmed that the thrust required by the E-Cutter has been fulfilled. However, it needs higher cutting time comparing to the *Cantas*™. It only needs about 2 seconds to finish the cutting by using the *Cantas*™ compared to about 6 seconds by using E-Cutter with the slot type of linear motor [1.26]. Therefore, in this research, focus will be given to design and develop new linear motor to function as actuator for the E-Cutter. The new linear motor should have at least similar thrust, F and total weight, W_{tot} however the mover responses need to be improved to reduce cutting time.

1.2 Objective

The aim of this research is to develop the linear motor to work as the E-Cutter's actuator. The linear motor should have high thrust characteristic within its restricted weight. Two types of linear motor have been designed and developed which are switched reluctance cylindrical linear synchronous motor (SRCLSM) and permanent magnet cylindrical linear synchronous motor (PMCLSM). As a guide line along the design stage, the design target are listed below :-

1. Thrust, F : > 200 N
2. Total weight, W_{tot} : ≤ 2.0 kg

1.3 Scope of Study

In this research, the E-Cutter's actuator was designed and developed. Furthermore, the aim of this research is to find appropriate linear motor type to be implemented as E-Cutter's actuator. There are two types of linear motor were considered which are switched reluctance cylindrical linear synchronous motor (SRCLSM) and permanent magnet cylindrical linear synchronous motor (PMCLSM).

Both types of linear motor were model using SolidWorks 2011 x64 Edition CAD software. Once the models of the linear motor have been established, it's were simulated using JMAG Designer (x64) version 13.0.02I. Each types of linear motor's structure were undergone structure design in order to maximize it performance. Once the appropriate parameters have been obtained, each types of linear motor were manufactured to validate the simulation result.

For the SRCLSM, the design stage start with a specific outline dimension. Three structure parameters have been varied to determine appropriate structure parameters. The structure parameters are air gap length, δ, teeth pitch, τ_p and ratio between teeth width, t_w and slot width, t_s. Each models of the SRCLSM was evaluated using thrust, F. The SRCLSM was intended to be designed in 6 phase. However, through the design and measurement stage, only single phase structure of the SRCLSM was considered. Based on the single phase performance, the 6 phase performance of the SRCLSM was estimated. Based on the estimated 6 phase performance, implementation feasibility of the SRCLSM to the E-Cutter actuator was observed.

For the PMCLSM, a 6 slot 8 pole structure topology was chose. The permanent magnet pitch, τ_{pm}, coil pitch, τ_c and air gap length, δ were fixed. Three structural parameters have been varied along the structural design. The structural parameters are shaft radius, r_s, height of permanent magnet, h_{pm} and height of coil, h_c. The structural parameters were varied within fixed of total radius, r_{total}. The total radius, r_{total} was fixed at 20 mm, 25 mm and 30 mm. A model of the PMCLSM with complies with targeted thrust, F and total weight, W_{tot} was observed and chose as the PMCLSM for the E-Cutter's actuator. Based on its performance characteristics, implementation feasibility of the PMCLSM to the E-Cutter's actuator was observed.

The design model of the SRCLSM and PMCLSM were then compared to commercialize permanent magnet linear motor. Three type of commercialize permanent magnet linear motor has been selected which are slot type linear motor, slot less type linear motor and shaft motor. Around 200 models of linear motor have been picked and performances of them were compared to the SRCLSM and PMCLSM performance. Four performance characteristics were used which are thrust, F, thrust constant, k_f, motor constant, k_m and motor constant square density, G.

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 basic concept of E-Cutter's actuator. This chapter start with introduction to the basic concept and operation of *Cantas*™ and E-Cutter. On top of that, brief of the *Cantas*™'s performance and it draw back as well as current status of E-Cutter development also were explained. Furthermore, introduction to both linear motor types which are the SRCLSM and the PMCLSM also being covered. The method to determine the design target for the linear motor also was discussed.

Chapter three describe the design and develop the SRCLSM. This chapter start with initial consideration of SRCLSM structure topology. After that, the structure of the SRCLSM was finalized by considering several parameters such as air gap length, δ, teeth pitch, τ_p and teeth width, t_w. The SRCLSM has been manufactured based on its final structure parameters. The performance characteristics of the SRCLSM were then measured and decision on feasibility to implement the SRCLSM as E-Cutter actuator was decided.

Chapter four covers the design and develop the PMCLSM. The design stage was started from selection of 6 slot 8 pole permanent magnet linear motor structure topology. The stator of the PMCLSM was set to slot type and slotless. Meanwhile several arrangements of permanent magnet magnetization were tested to select the appropriate permanent magnet magnetization direction for the PMCLSM's mover. In this chapter as well, measurement result of the PMCLSM characteristics was covered. The decision on feasibility to implement the PMCLSM as E-Cutter actuator also decided. Chapter Five presents a conclusion of the overall study and recommendations for future work.

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Chapter 2: Basic Concept of E-Cutter's Actuator

2.1 Mechanization of Oil Palm Harvesting Tool

Traditionally, the oil palm fruit fresh fruit bunches were harvested using a sickle. The sickle is attached to an aluminium pole. The length of the aluminium pole depends on the average height of the palm oil in the harvesting area. The sickle is placed at the base point of the bunch and the harvester will pull the aluminium pole several times to accomplish the cutting process. It took about 386 seconds to complete one cycle of harvesting activity [(2.1)]. By using traditional harvesting technique, it was recorded that the ratio of worker to the area of land (ha) was 1:18 and oil palm productivity was 11.60 tonnes/day [(2.2)]. However, the traditional harvesting technique consumes a lot of time of the harvester and could reduce the rate of harvester [(2.3) - (2.5)].

Over the years, numerous of researchers has been working out to introduce mechanizes harvester for various fruits. It was started about 1970s when human start to improve the productivity and encountering the shortage of the number of labor in the agricultural sector [(2.6)]. In 1983, A. M. Ramsay has discussed on the mechanization of raspberries in Scotland. Base on his findings, by applying mechanization at the raspberries plantation could improve the productivity over 10% compared to hand pickers harvesting [(2.6)]. G. Gianmetta and G. Zimnalatti, 1997, discussed a mechanical pruning system for Olive-Groves [(2.7)]. Based on this paper finding, the mechanical pruning could reduce the labour requirement from 128 man h/100 trees on hand pruning and 21 man h/100 trees for half mechanical pruning to 4 man h/100 trees. A mechanical system for apricots harvesting was designed and tested in [(2.8)]. Base on the test that has been conducted, the mechanical pruner could harvest about 1500 kg apricots compared to 450 kg and 22.50 kg by using traditional tools and hand picker respectively within 1 hour harvesting time. It is also increasing the number of trees harvested per minute up to 400 tree compared to 20 trees and 6 trees by using traditional tools and handpicked. A. Torregrosa *et al.*, 2009 through their paper has discussed the application of two type mechanizations to citrus harvesting in Spain. There are tractor shaker and trunk shaker using hand held pruner. The tractor shaker was most effective (72 % detachment) than hand-held shakers (57 %) [(2.9)].

By taking the inspire by the various mechanize harvesting system mentioned above, mechanization harvesting system for oil palm fruit system is come to idea to be realized. Before the harvesting system for oil palm fruit could be designed, the features of the fruit itself need to be studied. The oil palm fruits are normally compactly packed in a bunch. It is also hidden in the leaf axils in crowns and about 12 m height above the ground. Stalk of frond that underlying a bunch need to be cut first before the bunch could be harvested and fall freely on the ground [(2.1)]. The previous discussed mechanize of the harvesting system is implementing shake-catch mechanism [(2.6) - (2.9)]. All the fruits mention is having non-similarity with the oil palm fruit especially when the location and bunch type fruit are considered. The limited space between the fronds and bunches also made the shake-catch mechanism is unrealistic. Furthermore, implementing this technique made loose fruit numbers become higher hence increase the harvesting time especially during the time of collecting the loose fruit. Therefore, the bunch-harvested style is suggested to use in order to design and develop mechanize harvesting system for oil palm fruit [(2.1), (2.10)].

The Malaysian Palm Oil Board (MPOB) has initiated the mechanization of oil palm fruit harvester tools called as *Cantas*™. Figure 2.1 shows the structure of the *Cantas*™. The structure and mechanism of the *Cantas*™ is similar to sickle tools since it proven to be efficient enough so far in harvesting activities [(2.2), (2.11), (2.12)].

Figure 2.1 *Cantas*™ structure.

The *Cantas*™ consists of a 1.3 hp petrol engine located at the bottom of a telescopic aluminium pole. At the top, a sickle or a chisel will be attached and use as a cutting head. The telescopic aluminium length could be adjusted suit with the oil palm height made it suitable to be used in various height of oil palm. The rotational motion of the engine is transmitted through a transmission shaft located inside the telescopic aluminium pole to a pair of gears where the sickle is connected. These gears convert the rotational motion to linear oscillatory motion in order to vibrate the sickle. A con-rod mechanism activates the sickle to move up-down in its longitudinal direction, thus performing the cutting. The engine of *Cantas*™ has a working speed in the range between 3000 to 5000 rpm. With the engine speed, the sickle of *Cantas*™ has a maximum cutting displacement of 16 mm at 80 Hz of maximum cutting frequency [(2.2), (2.11), (2.12)]. The MPOB has setup several field testing session on the *Cantas*™ in commercial estates with the objectives of evaluating its performance and providing recommendations to the industry. As indicated in [(2.2)], the field testing has been done in Tereh Selatan Estate, located in Johor, Malaysia. Two teams of workers have been established during the testing session where one team was used sickle tool and the other used the *Cantas*™. Based on the field testing, by using the *Cantas*™, productivity of oil palm increased from 4.19 tonnes/day to 11.60 tonnes/day as compared to the manual sickles. Worker to land ratio (ha) also increased from 1:18 to 1:37. Despite of a good achievement by the *Cantas*™, this tool is found less efficient for height of oil palm more than 8 m. At this height of oil palm, the telescopic aluminium pole will start bends and making transmission of motion from the shaft to the cutting head ineffective [(2.2), (2.13)].

2.2 Basic Concept and Current Status of the E-Cutter Development

The mechanized oil palm fresh fruit bunch harvesting tools should be easy to handle, efficient enough and should improve the harvesting productivity. So far, the *Cantas*™ has proven it capability of improving the FFB harvesting activity base on the finding in [(2.2)]. However, the same productivity is only competent to maintain at height of oil palm up to 8 meters due to bending problem occurs in the *Cantas*™. Nevertheless, mechanized tools similar to the *Cantas*™ still could be considered as the best structure for higher oil palm. The farmer needs to engage the sickle to the base point of bunches before the harvesting activity could be accomplished. However, a flexible system should be designed so that the performance of the mechanized tools is not affected by the bending occurrence.

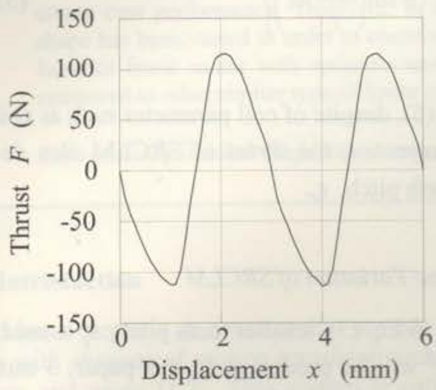
Harvesting activity done in horizontally could reduce the total thrust needed. Therefore, in the *Cantas*™, the MPOB adopted the vibrating mechanism that is transferred to a horizontal direction so that harvesting can be performed horizontally. Thus, a vibrating mechanism has therefore been designed and developed for the harvesting sickle which causes it to vibrate at high speed in the longitudinal direction of the pole’s axis. Therefore, similar structure of harvesting tool as *Cantas*™ was proposed. In the new tool, at least comparable performance of the *Cantas*™ but more flexible was aimed. Instead of mechanical based tool in the *Cantas*™, the new tool was designed in electrical based tool. The new tool is called as E-Cutter [2.13] - [2.15]. The basic structure of the E-Cutter is as shown in Figure 2.2. Since the structure of *Cantas*™ provides with several advantages especially on easiness to engage with the base of frond during the harvesting activity, the E-Cutter also maintain a similar structure of the *Cantas*™.

Figure 2.2 E-Cutter structure.

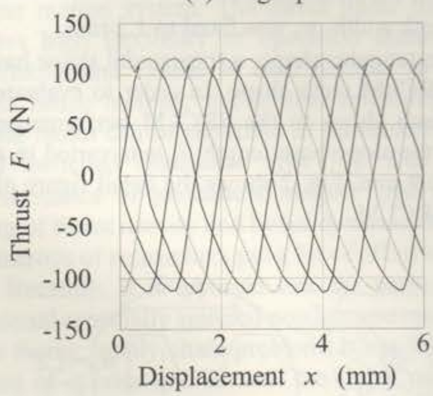
The 2 stroke engine used in the *Cantas*™ will still be used in the E-Cutter. However, the engine is attached to an electrical generator in order to convert the mechanical energy to electrical energy. On the top side of the E-Cutter, a linear motor is used in order to provide direct linear vibration motion to the sickle in order to accomplish the harvesting activity. A copper wire will be utilized to replace the shaft inside the aluminum pole in order to transmit the electrical energy provided by the electric generator to the linear actuator. Therefore, this tool will keep operating efficiently even though the pole is bending caused by the height increments due to the copper is more flexible to compare to the shaft in the *Cantas*™ [2.13] - [2.15].

The E-Cutter development progress depends on the development of the electrical generator and the linear motor. The development of the electrical generator seems to be established through several types of permanent magnet generator with different performance characteristics have been designed and developed [2.16] - [2.19].

The SRCLM is exciting by 1 phase excitation. Each phase of coil is exciting one by one. The sequence of excitation base on the phase number is 6-5-4-3-2-1. Fig. 4 shows the excitation sequence of SRCLM. Based on this excitation sequence, the six phase thrust characteristics is as shown in Fig. 5. The six phase thrust characteristics of all SRCLM models were plotted. Each model of SRCLM has been evaluated using average thrust, F_{ave}, thrust to weight ratio, F/W, thrust to volume ratio, F/V and thrust to power ratio, F/P.



(a) Single phase



(b) Six phase

Fig. 3 Thrust characteristics of SRCLM

4. Performance Comparison of SRCLM

4.1 Comparison between Similar Type of Linear Motor

The SRCLM models were evaluated using average force, F_{ave}, thrust to weight, F/W, thrust to volume, F/V and thrust to power ratio, F/P in order to search the optimum teeth shape. The teeth shape was differentiate using the slope base length, l_1.

Fig. 6 (a) shows the comparison of SRCLM average thrust, F_{ave}. It is shows that, the average thrust, F_{ave} of SRCLM is increase as the slope base length, l_1 is increase until it reach the maximum value at slope base length, l_1 equal to 0.2 mm. At the slope base length, l_1 is higher than 0.2 mm, the average thrust, F_{ave} is reducing significantly. Therefore, the best teeth shape of SRCLM is at slope base length, l_1 of 0.2 mm with average thrust, F_{ave} of 117 N.

The thrust to weight ratio, F/W and the thrust to volume ratio, F/V of SRCLM are as shown in Fig. 6 (b) and (c) respectively. By increment of slope base length, l_1 of SRCLM made increment the total volume and weight of SRCLM. However, each increment form each models is not too significant thus made these characteristics profile is not much different with the average thrust, F_{ave} profile. The highest thrust to weight ratio, F/W and thrust to volume ratio, F/V of SRCLM are 45.15 N/kg and 0.38×10^6 N/m^3 respectively.

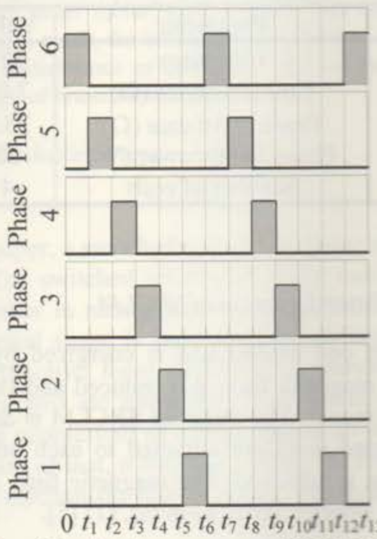


Fig. 4 Excitation sequence of SRCLM coil

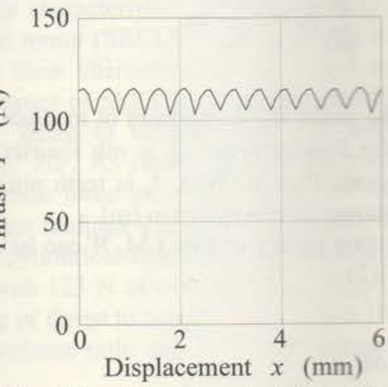


Fig. 5 Six phase characteristics of SRCLM

The input power of SRCLM was fixed to 50 W. Therefore, the profile of the thrust to power ratio, F/P is exactly the same as profile of average thrust, F_{ave} as shown in Fig. 6(d). The highest thrust to power ratio, F/P is obtained at slope base length, l_1 of 0.2 mm with value of 2.45 N/W.

All these performance characteristics of best model SRCLM is then compared to the other similar type of linear motor. In this case, the linear motor in [13], [14] and [15] were referred. Even though in [13] and [14], a linear pulse motor (LPM) were designed, however, due to similar structure to switched reluctance type of linear motor were used, these model was taken as comparison model. Furthermore, the performance of SRCLM is compared to common reluctance type performance. The comparison of performance characteristics is as shown in Table 2.

In [13], the pitch of mover has been set to 30 mm and six phase structure has been used. As a comparison, the SRCLM used the same number of phase but lower in term of the pitch. Based on Table 2, it is shown that, the performance characteristics of LPM in [13] is much lower compared to SRCLM. It is confirm with Eq. (5) that the thrust of switched reluctance motor is inversely to the pitch, τ_p.

The LPM in [14], is has better performance compared to the SRCLM in term of thrust to volume ratio, F/V and thrust to power ratio, F/P. This is due to use of permanent magnet in the LPM structure. By using the permanent magnet in the motor structure, higher thrust can be obtain over the same size hence increase the thrust to size ratio. However, the LPM in [14] is having lower in term of thrust to weight ratio, F/W compared to the SRCLM. Even though the lower pitch has been set in this LPM which 2.2 mm compared to the SRCLM, due to different of structure topology such as number of phase used, the thrust to weight ratio F/W of LPM [14] is lower than SRCLM.

In the switched reluctance linear motor (SRLM) in [15], the higher pitch has been used. The SRLM has been designed with 10 mm pitch and produced 0.25 × 10^6 N/m^3 compared to 0.38 × 10^6 N/m^3 produced by the SRCLM. However, the other performance characteristics are not reported in [15].

As shown in Table 2, the SRCLM not only having the best performance in term of thrust to weight ratio, F/W compared to other model, it also has been improved the common range of reluctance type performance. Even though the thrust to volume ratio, F/V and thrust to power ratio, F/P of the SRCLM are locates inside the common reluctance type performance range, however the value of both performances are locates near to the upper boundary of common reluctance type performance range.

4.2 Comparison of the SRCLM and Permanent Magnet Type of Linear Motor Performance.

The SRCLM performance also has been compared to permanent magnet type of linear motor (PMLM). There are three type of PMLM has been choose for comparison which are double magnet core type linear motor (DMC), permanent magnet coreless type linear motor (PMCL) and shaft motor. All of these PMLMs were selected from the commercialize PMLM from several linear motor manufacturer companies. Almost 200 PMLMs has been selected and their performance has been recorded.

The performance of PMLM normally measured by three performance indexes such as force constant, k_f, motor constant, k_m and motor constant square density, G [16]. These performance indexes were calculated using Eq. (6) - (8).

Fig. 7 shows the performance comparison between the SRCLM and the PMLMs. Apart of the three performance indexes that has been mention previously, the average thrust, F_{ave} also has been used in this comparison. All the performance indexes were plotted against their volume, V. Based on the Fig. 7, it is shown that, the SRCLM is have a capability to produce higher performance at similar volume, V compared to PMLM. The SRCLM is also seen having capability to produce higher thrust, F at smaller size and lower input power, P.

Table 2 Comparison of SRCLM with Similar Type of Motor Characteristics.

Performance	Best model SRCLM	LPM [13]	LPM [14]	SR [15]	Common Reluctance type
F/W (N/kg)	45.15	15.00	43.20	-	20 - 30
F/V (× 10^6 N/m^3)	0.38	0.075	0.43	0.25	0.06 – 0.40
F/P (N/W)	2.45	1.38	5.10	-	0.5 – 3.0

$$k_f = \frac{F}{I} \tag{6}$$

$$k_m = \frac{F}{\sqrt{P}} \tag{7}$$

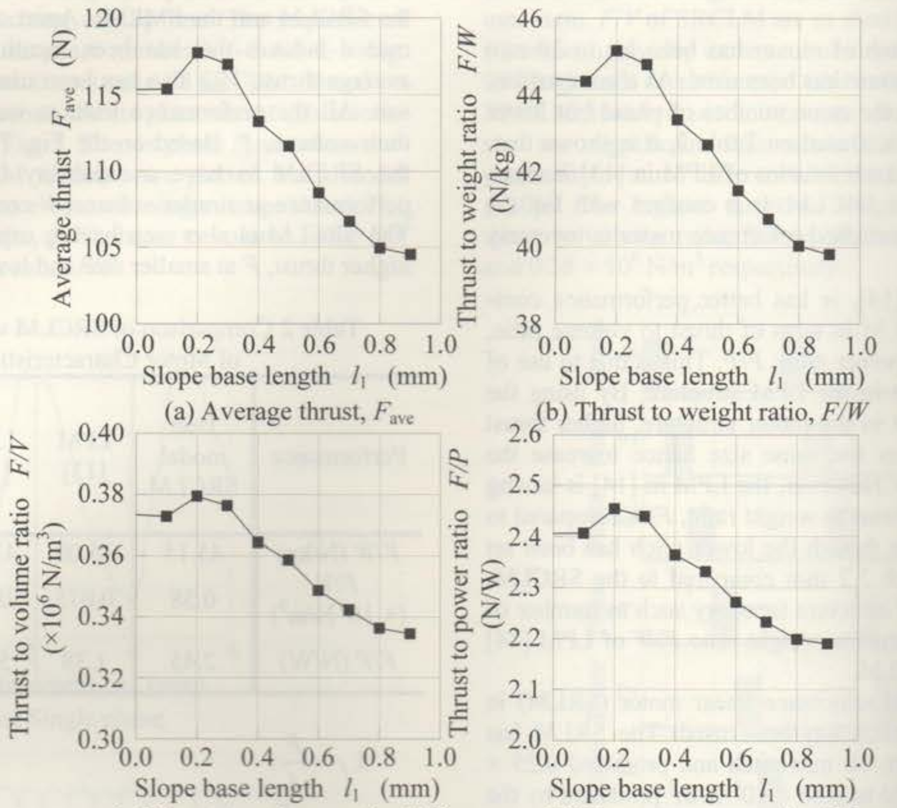
$$G = \frac{F^2}{PV} \tag{8}$$

Where k_f is the force constant in (N/A), k_m is the motor constant in (N/W$^{1/2}$), P is the input power in (W), G is the motor constant square density in (F^2/Wm^3) and V is the volume in (m^3).

5. Conclusion

In this paper, a non-permanent magnet type of linear motor was designed. The aimed of this paper is to improve the performance of switched reluctance cylindrical linear motor (SRCLM). From the analysis results, the following conclusions are obtained.

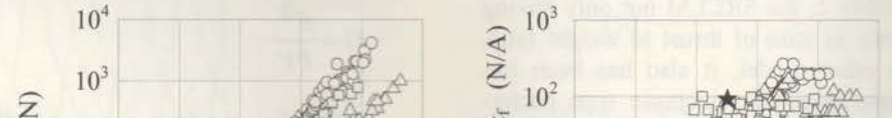
1. The teeth pitch, τ_p is playing a significant role in increase the thrust, F. as can be seen from the thrust comparison of the SRCLM with the LPM in [13].
2. The SRCLM has improved the performance of common reluctance type in term of thrust to weight ratio, F/W.
3. Even though the other two performance characteristics of SRCLM which are thrust to volume ratio, F/V and thrust to power ratio F/P are located in common reluctance type range performance, however its located near to the boundary of the range.
4. The SRCLM is capable to produce high thrust, F base on the comparison it performance indexes to the PMLM.



(a) Average thrust, F_{ave} (b) Thrust to weight ratio, F/W

(c) Thrust to volume ratio, F/V (d) Thrust to power ratio, F/P

Fig. 6 Performance comparison of SRCLM



(a) Thrust, F (b) Thrust constant, k_f

(c) Motor constant, k_m (d) Motor constant square density, G

Fig. 7 Comparison of SRCLM and PMLMs performance

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undergone laboratory and field testing to ensure performance. The performance characteristics of each linear actuator are as shown in Table III.

TABLE III. CHARACTERISTICS OF LINEAR ACTUATOR FOR E-CUTTER

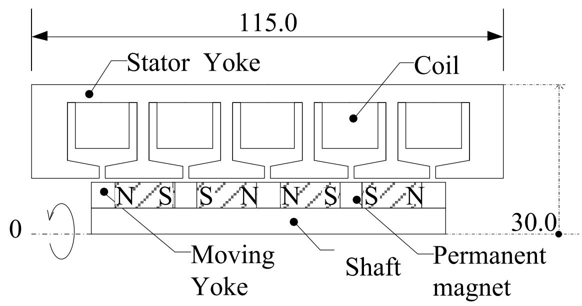
Type of linear actuator	Force (N)	Motor constant, k_m (N/W$^{1/2}$)	Motor constant square density, G (X 10^6 N^2/Wm^3)
Slot less [17]	50	8.5	0.58
Slot type [18]	100	22.1	1.97
Slot type [8,19]	222	32.5	3.40

IV. LINEAR ACTUATOR IMPROVEMENT PROGRESS

A. Previous Achievement of Linear Actuator Development

The latest linear actuator which was discussed in [8,19] was the E-Cutter's best performing linear actuator. The structure and construction of this actuator, known as STLOA-a, is as shown in Fig. 3. The STLOA-a was designed based on the target of having a minimum thrust of 200 N and a total weight of less than 2.0 kg. The thrust characteristics of the STLOA-a are as shown in Fig. 4. The details of STLOA-a's performances are listed in Table IV.

Based on the results of several testing sessions that have been carried out, it was determined that frond and bunch cutting was feasible. Fig. 5 shows the laboratory testing session carried out [8]. Several fresh oil palm fronds were brought to the laboratory and cut testing was performed. Based on the testing session, the STLOA-a has proven it can accomplish the cutting for various sized oil palm fronds.



(a) The STLOA-a structure (unit in mm)

(b) Construction of STALOA-a

Fig. 3 : Structure and construction of STLOA-a

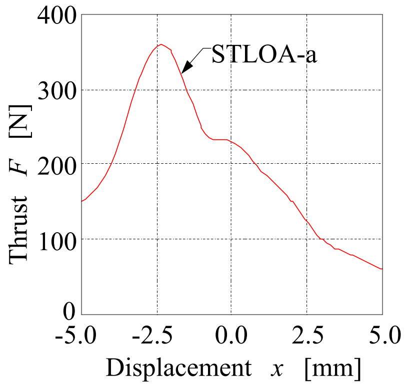
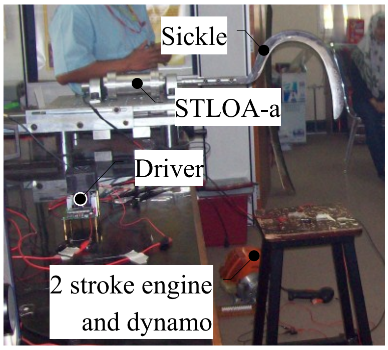


Fig. 4 : Thrust characteristics of STLOA-a



(a) Equipment setup for cutting evaluation

(b) During cutting evaluation

(c) Cutting process successfully done

Fig. 5 : Cutting evaluation of STLOA-a

B. Structure and Design Target for Linear Actuator Improvement.

In spite of its proven functionality, the STLOA-a has a slightly longer harvesting cycle time when compared to the *Cantas*™. The main drawbacks of the STLOA-a as compared to *Cantas*™ are the total displacement and oscillation frequency. From observation, the *Cantas*™ has a constant sickle vibration displacement of 16 mm and a frequency oscillation range between 60 Hz to 80 Hz depending on the position of the diesel engine throttle. In contrast, the STLOA-a has a total displacement of 9.39 mm and an oscillation frequency of 68 Hz. These characteristics will be a primary concern in E-Cutter linear actuator development without affecting the other performance characteristics. Table V shows the design target of the new linear actuator for the E-Cutter labeled STLOA-b.

TABLE IV. STLOA-A PERFORMANCE CHARACTERISTICS

Performance characteristics	Symbol	Unit	Value
Starting thrust	$F_{x=0}$	N	222
Maximum thrust	F_{max}	N	360
Minimum thrust	F_{min}	N	60
Dimension	d	mm	115 × Φ60
Weight	W	kg	2.0
Thrust constant	k_f	N/A	58.15
Motor constant	k_m	N/√W	32.5
Motor constant square density	G	$\times 10^6$ N^2/Wm^3	3.40
Displacement	x	mm	9.39
Oscillation frequency	f_{osc}	Hz	68
Electrical time constant	τ_e	ms	8.12
Mechanical time constant	τ_m	ms	2.75

TABLE V. COMPARISON OF STLOA A-A AND STLOA-B SPECIFICATION

STLOA-a [8,19]		STLOA-b	
Starting thrust	222 N	Average thrust	222 N
Thrust constant	58.15 N/A	Thrust constant	58.15 N/A
Total weight	2.0 kg	Total weight	2.0 kg
Displacement	10 mm	Displacement	16 mm
Oscillation frequency	68 Hz	Oscillation frequency	80 Hz

For the STLOA-b, the 3 phase linear actuator will be designed compared to the previous single phase type STLOA-a. The 3 phase type was chosen because it provides relatively low ripple thrust, ease of displacement and motion direction control by reversing the 3 phase sequence.

In the STLOA-a, an anti-parallel permanent magnet arrangement was used. The purpose of using this arrangement was to double up the magnetic flux density inside the air gap. However, for the STLOA-b's design and development, a halbach array of permanent magnets will be used to control their magnetic flux path direction and increase efficiency. The structure of STLOA-b is as shown in Fig. 5. The stroke of STLOA-b is in the Y-axis direction. The permanent magnet and coil pitch are set to 11.25 mm and 15 mm respectively. A three phase current with an amplitude of 1.66 A and a frequency of 70 Hz were used to energize the STLOA-b. The coil turns were set to 704 with a coil resistance of 18.26 Ω.

C. Initial Findings Comparison of Linear Actuator Improvement.

The STLOA-b model was simulated in order to evaluate the performance. The full displacement of thrust characteristics of STLOA-b is as shown in Fig. 6. It has a maximum thrust, F_{max} of 208 N, a minimum thrust, F_{min} of 92 N and an average thrust, F_{ave} of 142.4 N. The comparison details of STLOA-a and STLOA-b performance characteristics are as listed in Table VI.

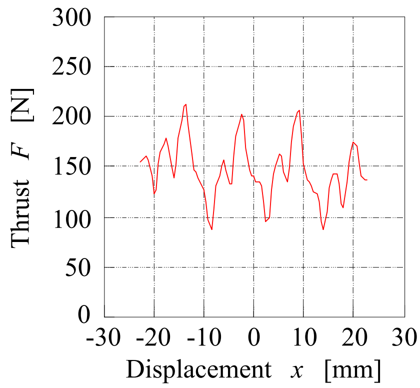


Fig. 6 : Thrust characteristics of STLOA-b

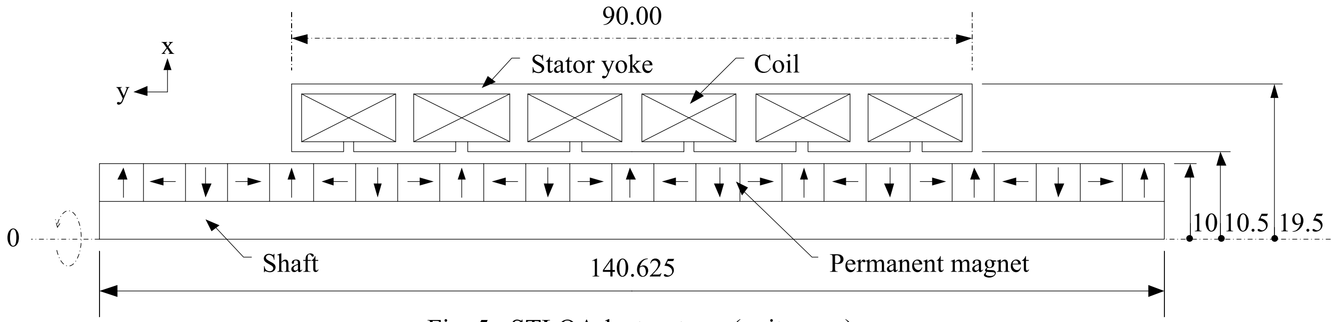


Fig. 5 : STLOA-b structure (unit : mm)

TABLE VI. COMPARISON OF STLOA-A AND STLOA-B PERFORMANCE CHARACTERISTICS

Performance characteristics	Symbol	Unit	STLOA-a	STLOA-b
Maximum thrust	F_{max}	N	360	208
Minimum thrust	F_{min}	N	60	92
Weight	W	kg	2.0	0.95
Thrust constant	k_f	N/A	58.15	125.65
Motor constant	k_m	N/√W	32.5	20.80
Motor constant square density	G	$\times 10^6$ N^2/Wm^3	3.40	4.00
Electrical time constant	τ_e	ms	8.12	0.18
Mechanical time constant	τ_m	ms	2.75	0.48

Based on table VI, the maximum thrust, F_{max} of STLOA-b has been reduced 42.2% when compared to the maximum thrust, F_{max} of STLOA-a. However, the increment of minimum thrust, F_{min} of STLOA-b is as much as 53.5% when compared to the minimum thrust, F_{min} of STLOA-a. This proves that the 3 phase linear actuator could relatively reduce thrust ripple. Even though the average thrust, F_{ave} of STLOA-b does not yet meet the design target of about 35.8%, it structure size could possibly be increased since the weight of STLOA-b is far below the design target.

The thrust constant represents the ratio between the injected current and the average thrust developed. The higher value of thrust constant indicates that higher thrust could be produced with the same excitation current value. The thrust constant, k_f of STLOA-b was calculated using (1). As shown in table VI, the STLOA-b has a greater thrust constant value, k_f compare to STLOA-a by about 116.08%, from 58.15 N/A to 125.65 N/A.

$$k_f = \frac{F_{ave}}{I_{rms}}, \text{ N/A} \tag{1}$$

Where k_f is the thrust constant in N/A, F_{ave} is the average thrust in N and I_{rms} is the RMS value of the excitation current in A.

The motor constant, k_m, is used to evaluate the ratio between thrust and input power. The higher the value of the motor constant, k_m, the higher the thrust of the linear actuator with the same input power. The motor constant, k_m of STLOA-b was calculated using (2). But in this case, the motor constant, k_m of STLOA-b was lower by 56.25% when compared to STLOA-a. Nevertheless, this parameter is expected to increase as structural and thrust optimization is done.

$$k_m = \frac{F_{ave}}{\sqrt{P_{in}}}, \text{ N/}\sqrt{\text{W}} \tag{2}$$

Where k_m is the motor constant in N/√W, F_{ave} is the average thrust in N and P_{in} is the input power of the linear actuator in W.

The motor constant square density, G, is used to estimate the ratio between thrust, input power and the size of the linear actuator. The higher the value of the motor constant square density, G, the higher the thrust of the linear actuator with the same input power and size. The motor constant square density, G of STLOA-b was calculated using (3). In this case, the motor constant square density, G of STLOA-b was higher by 17.65% when compared to STLOA-a. The motor constant square density, G, of STLOA-b and STLOA-a were 4.00×10^6 N^2/Wm^3 and 3.40×10^6 N^2/Wm^3 respectively.

$$G = \frac{{k_m}^2}{v} = \frac{{F_{ave}}^2}{P_{in} v}, \text{ N/}\sqrt{\text{W}} \tag{3}$$

Where G is the motor constant square density in N^2/Wm^3, k_m is the motor constant in N/√W, v is the volume of the linear actuator in m^3, F_{ave} is the average thrust in N and P_{in} is the input power of the linear actuator in W.

The electrical time constant, τ_e is used to evaluate the current response of a linear actuator. The lower the value of the electrical time constant, τ_e, the faster the response of the current. The current will reach its final value when the inductance no longer affects the response of the current, corresponding to the frequency of the power supply in a short time. The electrical time constant, τ_e, of STLOA-b was calculated using (4). The design target for the electrical time constant, τ_e, depends on the frequency of the power supply, f and the mover's oscillation, f_{osc} of STLOA-b. In order to make the STLOA-b operates similar to a *Cantas*™, the frequency of mover's oscillation, f_{osc} of STLOA-b was targeted to equal 80 Hz. Since the total displacement target is 16 mm, the velocity of the mover is estimated to be equal to 1.28 m/s. Based on several simulation trials, the appropriate frequency of the power supply for STLOA-b, f is 70 Hz. Therefore, the electrical time constant, τ_e, of STLOA-b needs to be less than half of the complete cycle time of the power supply which is 7.14 ms.

$$\tau_e = \frac{L}{R}, \text{ ms} \tag{4}$$

Where τ_e is the electrical time constant in ms, L is the coil inductance in mH and R is the coil resistance in Ω.

The mechanical time constant, τ_m, is used to evaluate the mover response of the linear actuator. The lower value of the mechanical time constant, τ_m, means a faster mover response. The mover as well will reach the desired final displacement in a short time. The mechanical time constant, τ_m, of STLOA-b was calculated using (5). As discussed, the oscillation frequency, f_{osc} of STLOA-b was targeted to equal 80 Hz. The total displacement target is 16 mm and the mover velocity is estimate to equal 1.28 m/s. Therefore, the mechanical time constant, τ_m, of STLOA-b needs to be less than half of the complete cycle time of the oscillation which is 6.25 ms.

$$\tau_m = \frac{mR}{{k_f}^2}, \text{ms} \quad (5)$$

Where τ_m is the mechanical time constant in ms, m is the mover weight in mH, R is the coil resistance in Ω and k_f is the thrust constant in N/A.

Based on these observations, there are some characteristics of STLOA-a that have been improved by the STLOA-b such as the thrust constant, k_f, the motor constant square density, G, the electrical time constant, τ_e and the mechanical time constant, τ_m while the other characteristics seem to be reduced especially for the average thrust. Yet, since the total of weight of STLOA-b is much lower as compared to its design target, design optimization is possible to increase the parameter between weight restrictions.

V. CONCLUSION

World demand for palm oil products has been increased year over year. Therefore, increasing production is essential to ensure its availability in the market. To achieve this, one aspect could be to improve harvesting. In Malaysia, research to improve productivity of oil palm fresh fruit bunch (FFB) harvesting has begun by the Malaysia Palm Oil Board (MPOB). The MPOB has invented a new mechanized harvesting tool called the *Cantas*™. *Cantas*™ has demonstrated impressive improvements in oil palm FFB harvesting output. Yet, improvements need to be done due to height limitations that affect the operation of *Cantas*™. Thus the E-Cutter was introduced. The E-Cutter solves the operation limitation of *Cantas*™ due to a part elimination in the transmission shaft which causes the operation limitation of the *Cantas*™. The progress of E-Cutter development is discussed in this paper. The main concern was progress with the linear actuator as it is a key success point for E-Cutter development. The STLOA-a linear actuator of the E-Cutter has been established previously. Several tests conducted prove that the STLOA-a could perform the required harvesting activity. Improvement to the STLOA-a is essential, especially to improve dynamic operation of the E-Cutter. Therefore, a new linear actuator for the E-Cutter is required. The initial findings and the possibility of improving E-Cutter operation was discussed in this paper.

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