UNIVERSITI PUTRA MALAYSIA

COMBINED AXIAL AND LATERAL ROTARY CUTTING MECHANISM FOR CHOPPING OIL PALM FROND

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FK 2017 121

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By

WADHAH NOORI HUMADI ALNUAIMI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

April 2017

DEDICATION

I would like to dedicate my thesis to

My father soul

and

A special feeling of gratitude to

My loving mother

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Doctor of Philosophy

COMBINED AXIAL AND LATERAL ROTARY CUTTING MECHANISM FOR CHOPPING OIL PALM FROND

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April 2017

Chairman : Associate Professor Rimfiel bin Janius, PhD
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The oil palm frond (OPF) is one of the most abundant agricultural by-products in Malaysia and has great potential to be utilized as mulch, fuel, animal feed constituent and fertilizer constituent. Today, it is also an important resource in various modern industries such as pulp and paper, fiberboard and biodegradable film. However, these benefits could not be realized fully due to the absence of a suitable way of reducing the size of the fronds conveniently and economically. Moreover, the high cost of size reduction machines due to high-power requirement, large size and lack of mobility inside the field cause the farmer to bear the transportation costs of moving oil palm fronds outside the field to chop. This necessitated the need to design a new cutting mechanism which commensurate with the physical and mechanical properties of oil palm fronds in order to get the best performance with less energy consumption. Hence, this will reduce the cost of the machine and increase farmer's income through the sale of the chopped materials.

The aim of this research is to develop a cutting mechanism that can chop oil palm fronds completely and efficiently. The specific objectives are 1) to investigate the physical properties and mechanical strength of oil palm fronds 2) to formulate a slicing-chopping mechanism and to investigate the mechanics involved and 3) to evaluate the performance of a physical compound knife employing the formulated mechanism. The properties and strengths of OPF were investigated at two levels of moisture content (72% and 59%) and two levels of maturity (5 and 10 years). A slicing-chopping mechanism consisting of compound lateral and axial blades was then formulated to split the OPF lengthwise to many strips before cutting them one by one to make the cutting process sequentially rather than simultaneously in order to reduce the energy required. The mechanics involved was investigated in detail from which three different sets of compound knives consisting of 4, 5 and 7 axial blades were fabricated. Validation of the models was done by running the knives to

chop OPF at the various treatment levels stated above at speeds of 1500 and 1900 rpm and the operating torque, power requirement, throughput capacity and chopping rate measured.

Results of strength tests revealed that the stalk is the strongest part of an oil palm frond irrespective of moisture content and maturity. While the lateral shear force is directly proportional to the moisture content, the axial (lengthwise) shear force and the penetration force are inversely proportional to moisture content. Moisture content has a very strong influence on the shear strength of oil palm fronds but not on compressive strength. Maturity consistently has the smallest effect on penetrative, compressive, lateral and axial shear forces. The force required to cut oil palm frond stalks by the lateral blade only (i.e. the conventional way) was about twice more than by the compound knives irrespective of the moisture content and maturity of the fronds. A compound knife with 5 axial blades powered by a petrol engine of 2.8 kW (3.7hp) rated power was able to chop fronds completely right up to the stalk at 1500 rpm. The highest power requirement was obtained when running the 7-axial-blade compound knife at 1900 rpm; being 4.7 kW (6.3 hp). A maximum chopping capacity of 1059 kg/h was obtained using a compound knife with 5 axial blades at 1900 rpm.

In conclusion, the slicing-chopping mechanism developed was proven to be able to chop OPF completely up to the stalks and with about 50% less energy, both of which have never been achieved by any commercially available OPF choppers before.

This work contributes knowledge on the development of a compound blade that can chop the whole OPF up to the stalk using engine power of less than 3 kW, both of which have never been possible before. Besides it also contributes to the literature in similar works on the development of chopping machine and forage harvesting related machines and expanding the new idea on using new technology and work successfully on the field.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

GABUNGAN MEKANISMA PEMOTONGAN SISI DAN BERPAKSI BAGI MENCINCANG PELEPAH KELAPA SAWIT

Oleh

WADHAH NOORI HUMADI ALNUAIMI

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Pelepah kelapa sawit (OPF) adalah salah satu daripada bahan sampingan industri pertanian yang paling banyak di Malaysia yang mempunyai potensi yang besar untuk digunakan sebagai mulsa, bahan api, komponen makanan haiwan dan komponen baja. Kini, pelepah kelapa sawit (OPF) adalah salah satu sumber yang penting dalam pelbagai industri moden seperti pulpa dan kertas, papan serat dan filem biodegradable. Walau bagaimanapun, manfaat ini tidak dapat direalisasikan sepenuhnya kerana kos untuk mengurangkan saiz pelepah dengan mudah dan berekonomikal. Selain itu, kos menghasilkan mesin yang dapat mengurangkan saiz adalah tinggi kerana keperluan kuasa kuda yang tinggi, saiz ladang yang besar dan kekurangan mobiliti dalam ladang membuat petani menanggung kos pengangkutan yang tinggi untuk alih pelepah kelapa sawit ke luar ladang untuk dicincang. Ini membawa kepada keperluan untuk mereka cipta satu mekanisme baru untuk memotong pelepah kelapa sawit yang sesuai dengan sifat-sifat fizikal dan mekanikalnya untuk mendapatkan prestasi yang terbaik dengan penggunaan tenaga yang minima. Oleh itu, ini akan mengurangkan kos mesin dan meningkatkan pendapatan petani melalui penjualan bahan yang dicincang.

Tujuan penyelidikan ini adalah untuk membangunkan mekanisme pemotongan yang boleh mencincang daun kelapa sawit dengan sempurna dan cekap. Objektif khusus penyelidikan ini adalah 1) untuk mengkaji sifat- sifat fizikal dan kekuatan mekanik pelepah kelapa sawit 2) untuk merumuskan mekanisme hiris-cincnag dan menyiasat mekanik yang terlibat dan 3) untuk menilai prestasi fizikal pisau yang menggunakan mekanisme yang dirumuskan.

Sifat dan kekuatan pelepah kelapa sawit dikaji pada dua tahap kandungan kelembapan (72% dan 59%) dan dua tahap kematangan (5 dan 10 tahun). Mekanisme pencincang terdiri daripada pisau sisi dan pisau berpaksi kemudian direkacipta untuk memotong OPF secara memanjang kepada banyak jalur sebelum memotong mereka satu demi satu dalam proses pemotongan berurutan dan bukannya pemotongan serentak untuk mengurangkan tenaga yang diperlukan. Mekanisma yang terlibat disiasat secara terperinci dengan menggunakan tiga set pisau kompaun yang terdiri daripada 4, 5 dan 7 bilah pisau berpaksi. Pengesahan model dilakukan dengan mengendalikan mekanisme memotong pelepah kelapa sawit di pelbagai tahap yang dinyatakan di atas pada kelajuan 1500 rpm dan 1900 rpm dan mengukur kadar pusingan pemotong, keperluan kuasa, kapasiti pemprosesan dan kadar mencincang.

Keputusan ujian kekuatan mendedahkan bahawa bahagian tangkai adalah bahagian yang paling kuat daripada pelepah kelapa sawit tanpa mengira kandungan kelembapan dan kematangan. Manakala daya potongan sisi adalah berkadar terus dengan kandungan kelembapan, daya pemotongan berpaksi (memanjang) dan daya penembusan pula adalah berkadar songsang dengan kandungan kelembapan. Kandungan lembapan mempunyai pengaruh yang sangat kuat pada kekuatan mencincang pelepah kelapa sawit tetapi tidak mempunyai kesan yang besar kepada daya mampatan. Kematangan secara konsisten mempunyai kesan minima ke atas daya penebusan, mampatan, pemotongan sisi dan berpaksi. Daya yang diperlukan untuk memotong pelepah kelapa sawit menggunakan pisau sisi (cara konvensional) adalah kira-kira dua kali lebih banyak daripada dengan pisau kompaun tanpa mengira kandungan kelembapan dan kematangan pelepah. Satu pisau sebatian yang terdiri daripada 5 paksi yang beraksi dengan menggunakan kuasa enjin petrol 2.8 kW (3.7hp) dapat memotong pelepah kelapa sawit ke tangkai pada kelajuan 1500 rpm. Keperluan kuasa tertinggi didapati ketika menjalankan pisau sebatian 7 bilah berpaksi pada kelajuan 1900 rpm; iaitu 4.7 kW (6.3 hp). Kapasiti pemotongan maksima sebanyak 1059 kg / j diperoleh dengan menggunakan pisau sebatian 5 bilah berpaksi pada kelajuan 1900 rpm.

Kesimpulannya, mekanisme pemotongan mencincang terbukti dapat memotong OPF sepenuhnya sehingga tangkai dan menggunakan 50% kurang tenaga. Dua kelebihan ini tidak pernah dicapai oleh mana-mana pencincnag pelepah kelapa sawit komersial yang sedia ada.

Selain itu, kajian ini menyumbang kepada kajian kesusasteraan dalam bidang pembangunan mesin yang berkaitan dengan pencincang dan penuaian serta mengembangkan idea baru tentang penggunaan teknologi baru dan bekerja dengan jayanya di ladang.

ACKNOWLEDGEMENTS

All praise and glory is due to Almighty Allah (the Most Gracious, the Most Merciful, the Omnipotent and Self-Subsistent) for Allah grace and gave me opportunity towards the success and completion of this work.

I would like to extend my heartfelt gratitude to the many people who have contributed to this project in the form of assistance, ideas and critiques.

Firstly, I would like to thank my supervisor **Associate Professor Rimfiel bin Janius** for accepting me as a PhD student. I am truly indebted to his insights during discussions, and for his patience to teach and to review my writings that are often riddled with grammatical errors. He was a source of inspiration with his encouragement, helpful suggestions, valuable guidance and unwavering support at times of technical failures and intellectually challenging findings.

I am immensely grateful to my Co-supervisor **Professor, Ir Desa bin Ahmad** who provided the opportunity and support to pursue my interest in research.

I am also greatly indebted to my Co-supervisor **Dr. MD. Akhir bin HJ. Hamid** for his support, advice, and contribution.

This work would not be completed without the support of staff and researchers of the Faculty of Engineering and Mardi Institute. Special thanks go to the technical staff of department of biological and agricultural laboratories at faculty of engineering and the technical staff laboratories at Mardi Institute for efforts in manufacturing and maintaining test equipment.

I certify that a Thesis Examination Committee has met on 28 April 2017 to conduct the final examination of Wadhah Noori Humadi on his thesis entitled "Combined Axial and Lateral Rotary Cutting Mechanism for Chopping Oil Palm Frond" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

OPF	oil palm fronds
OPT	oil palm trunks
EFB	empty fruit bunch
million-t/y	million-tone/year
TEM	Transmission electron microscopy
µm	Micrometer
l/d	aspect ratio of fiber
Hp	Hours Power
rpm	Roller Rotor Speed
LRE	edge radius
LTE	edge thickness
ANEB	wedge angle of blade
LTB	blade thickness
LWB	blade width
LTC	thickness cut layer, total
FOC	cutting force
SLK	knife travel coordinate
FOCS	Specific cutting force
LWC	width of cut
ENC_1	cutting energy
FOCAV	average cutting force during one cut
ENCS	specific cutting energy

ENC	total cutting energy for cutting the amount MA
MA	amount of dry matter cut
POC	power used for cutting
MAT	device capacity as dry matter
ANR	rake angle
ANC	clearance angle
ANP	chip angle
ANT	tilt angle
ANS	slant angle
POD	total power for the cutting device
P0L1	non-cutting power loss
EFC	cutting efficiency, fraction
POC	actual cutting power
ASABE	American Society of Agricultural and Biological Engineering
ANSI	American National Standards Institute
M%	moisture content percentage
W_w	wet weight
W_d	dry weight
^oC	Temperature(centigrade)
KN	kilonewton
F_w	Force necessary to cut material, in the section plane
K_{mt}	Resistance of material to shear
S_{mt}	Area of the cut cross-section
τ_t	Shear stress at shearing

SCF	specific cutting force
SCE	specific cutting energy
F_{max}	Maximum cutting force
E_{max}	maximum cutting energy
A_{max}	maximum cross section area of OPF stem
Me	microstrain
P_{rot}	rotational mechanical power
M	torque
Ω	angular velocity

CHAPTER 1

INTRODUCTION

1.1 Overview of Oil Palm Fronds (OPF)

Oil palm is one of the most important commodity crops in Malaysia. Mature palms are single-stemmed and grow to 20 m tall. The fronds are pinnate and reach between 3-9 m long. A young palm produces about 30 fronds a year. Established palms over 10 years old produce about 20 fronds a year.

The oil palm frond (OPF) is one of the most abundant agricultural by-products in Malaysia. It is obtained from the cultivation of oil palm trees (Elaeis guineensis Jacq). Almost all pruned fronds are discarded in the plantation, mainly for nutrient recycling and soil conservation. It has great potential to be utilized as a roughage source or as a component in compound feed for ruminants.

Yuen and Aziz (2012) reported that the total planted area of oil palm in 1990 reached 2,094,028 million hectares. In the year 2011, the total planted area of oil palm was 5,642,943 million hectares (MPOB, 2015). This increase in planted area means an increase in plant biomass and the biggest part of this biomass is oil palm fronds. It is estimated that 47 million tons of oil palm fronds (OPF) are produced in 2011 in Malaysia from 5 million hectares of plantation (MPOB, 2015).

This number is estimated to have risen with the increase in hectarage under oil palm. The OPF is rich in fiber and many minerals like N, P, K, and Mg. Moreover, it can be used as mulch, fuel, animal feed constituent and fertilizer constituent. In addition to that, it also is an important resource in various modern industries such as pulp and paper, fiberboard and biodegradable film. However, these benefits could not be realized fully due to the absence of a suitable way of reducing the size of the fronds (Hamid, 2008).

According to Abu Hassan et al. (1996), the interest in the use OPF as animal feed have caused many research to be carried out by the Malaysian Agricultural Research and Development Institute (MARDI) and the Japan International Research Center for Agricultural Sciences (JIRCAS).

Detailed studies on the fermentation characteristics and palatability of OPF silage as well as on animal performance have been positively reported by Abu Hassan and Ishida (1991), Ishida and Abu Hassan (1997) and Shio et al. (1999). Nevertheless, oil palm frond (OPF) is still limited in its use despite the aforementioned developments.

In the 1990s, oil palm fronds and trunk wastes used to be burned. But environmental concerns led to the banning of such practice (Zainal et al., 2000). Currently, for the long-term benefit of nutrient recycling the OPF are left to rot between the rows of palm trees mainly for soil conservation and erosion control. Ultimately the disadvantages of this practice are the spread of diseases, the harboring of dangerous animals, the trapping of loose fruits and being unsightly.

1.2 Oil Palm Frond (OPF) Size Reduction Machines

None of the currently available commercial size reduction machines or choppers is specifically designed for oil palm fronds. They are typically big, of high power requirement, expensive and, as they are actually foraging choppers, can chop up to about a half of the length of the fronds only. In the absence of other alternatives for disposal, as discussed in section 1.1 above, the farmer has no choice but to maintain the status quo, i.e. pile the fronds up in alternate rows in the field. This is because the main goal of the farmer is profit and he/she will try to reduce production costs as much as possible.

Biomass pretreatment or chopping is a very expensive operation with high energy demand. Reducing energy requirements improves the whole process economics. Generally, the energy requirement of mechanical comminution depends on the machine type, operating variables, particle sizes (initial and final), biomass characteristics, processing amount, composition and moisture content.

The characteristics of OPF are the key to the development and optimization of a cutting mechanism that commensurates with the physical and mechanical properties of OPF. The fiber-packed and strong broad end of the frond is acutely curved and this makes chopping even more difficult. Hence the concept of dividing the stem of OPF frond by installing the axial blades on the lateral blade in order to reduce the chopping force requirement of the frond, in addition to make the cutting process sequentially rather than cumulative to cut part by part until the end cross-section of the frond in one pass. An appropriately designed cutting mechanism would lead to high performance, reducing expenses in the attempt to arrive at the best solution in dealing with this biomass.

1.3 Problem Statement

A huge amount of oil palm fronds (OPF) is accumulated in the field after harvesting. Left in the field, they act as mulch but also house rodents and snakes, trap loose fruits, help in the spread of diseases and are unsightly.

The relatively large size of the fronds make the cost of transportation to take them out of the field to be about RM10 per kilometer per ton (Gomes, 2011; Rozario and Melssen, 2013) while burning them will cause environmental concerns. Being rich in minerals and fiber, the OPF can be used not only as mulch, fuel, animal feed constituent and fertilizer constituent but also as an important resource in various modern industries such as pulp and paper, fiberboard and biodegradable film. However, these benefits could not be realized fully due to the pre-processing cost being around RM150 to RM430 per ton (Rozario and Melssen, 2013) to reduce the size to 2-3 cm as per the required demand (Zahari et al., 2002). Also, currently available frond chopping machines are able to cut the slim part of the frond only, not right up to the broad end which contains a lot of useful material. These machines are manufactured to cater for a wide range of agricultural residues, making their power requirement to be around 22 kW (30 horsepower). The absence of a suitable way of reducing the size of the fronds effectively and economically is mainly due to the mechanics of chopping the fiber-packed OPF being still not understood. Therefore, there is a need to develop an appropriate cutting mechanism with a design that commensurate with the physical and mechanical properties of oil palm fronds in order to get the best performance with the least energy consumption. An appropriately designed cutting mechanism would be able chop the whole frond right up to the broad end.

1.4 Aim and Objectives

The aim of this study is to develop a suitable cutting mechanism for chopping oil palm fronds. The specific objectives are:

1. To investigate the physical properties and mechanical strengths of oil palm fronds.
2. To formulate a slicing-chopping mechanism for oil palm fronds and to investigate the mechanics involved.
3. To evaluate the cutting performance of physical knife models employing the formulated slicing-chopping mechanism by fabricating compound knives with different slicing blade distances and running them to chop OPF at various frond and machine variables.

1.5 Scope of Study

This study focuses on the development of the cutting mechanism only because chopping is the biggest problem and its mechanics has never been understood. The forces involved and the most effective method of cutting was investigated. Therefore, while the appropriate dimensions of the cutting mechanism and the materials used were considered, a full engineering analysis of strength for optimal design was not carried out. Also studied were the physical and mechanical properties of oil palm fronds. The design and development of a whole commercial oil palm frond chopping machine were not covered; as such mechanical feeding was not studied. Also not included in the scope of the study was the mechanical picking up and transporting of the fronds from the field.

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