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USE OF TRIPLE FLAT-TYPE AIR COIL INDUCTIVE RESONANCE AS AN OIL PALM FRUIT MATURITY SENSOR

NOR AZIANA BINTI ALITEH

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By

NOR AZIANA BINTI ALITEH

Thesis Submitted to the School of Graduates Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

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USE OF TRIPLE FLAT-TYPE AIR COIL INDUCTIVE RESONANCE AS AN OIL PALM FRUIT MATURITY SENSOR

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Chairman : Norhisam bin Misron, PhD
Faculty : Engineering

Conventionally, a human inspector is used to inspect the ripeness of oil palm fresh fruit bunch (FFB) which can be inconsistent and inaccurate. There are various new methods that are proposed to grade the ripeness of the oil palm FFB such as spectroscopy imaging techniques. This research aims to improve the oil palm maturity detection inductive resonance method using triple series flat-type air coil. The first objective of this research is to design triple flat-type air coil for oil palm fruit maturity sensor. Besides that, the thesis also aimed to investigate the relationship between oil palm fruitlet sample resonance frequency and fruitlet capacitance against progressing week and moisture content. In addition, its effectiveness with single flat-type air coil configuration is compared in terms of sensitivity and precision in order to select the best triple series flat-type air coil among two types of coil series tested. The method used for oil palm fruit maturity detection in this study is inductive sensor concept based on a resonant frequency technique. From the resonant frequency value, the fruitlet capacitance is identified by subtracting the self-capacitance of the coil with the sample and without the sample. There are three types of evaluation used in this study, namely: direct ripe-unripe, week, and moisture comparison. From these three evaluations, the differences between ripe and unripe were identified and compared. The sensitivity performance was assessed using the differences value and the precision was assessed by using the value of the coefficient of variation c_V. Based from the results obtained, the peaks from inductance-frequency curve shifted closer to the peak curve of the air as the oil palm fruitlet ripens but the fruitlet capacitance decreased as the oil palm fruitlet matures due to the reduction of moisture content in the fruitlet. Depending on the coil configuration, the triple series technique was able to influence its sensitivity obtained in comparison to the single flat-type coil structure. The Triple I, a triple series coil with fixed number of turns N=200 with different length (3mm, 5mm, 10mm), showed better results than the Triple II coil with fix length l=5mm and different number of turns (N=140, 200, 400). Triple I and II also

improved the sensitivity performance of its equivalent single coil by 353% and 63% respectively for 1st peak resonance frequency average differences. In addition, Triple I also proved to be more precise with small average coefficient of variation value for all three peaks (c_V=0.2284) when compared to Triple II (c_V=0.8401). In conclusion, the development of this sensor proves the capability of inductive elements such as coil to be used as a detection element to determine the ripening stages of the oil palm FFB sample.

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

PENGGUNAAN ARUHAN RESONANS TIGA GEGELUNG TERAS UDARA JENIS RATA SEBAGAI PENDERIA KEMATANGAN BUAH KELAPA SAWIT

Oleh

NOR AZIANA BINTI ALITEH

Mei 2018

Pengerusi : Norhisam bin Misron, PhD
Fakulti : Kejuruteraan

Penggredan kematangan tandan buah kelapa sawit segar (FFB) secara konvensional menggunakan pemeriksa manusia boleh menyebabkan pemilihan yang tidak konsisten dan tidak tepat. Terdapat pelbagai kaedah baru yang telah dicadangkan untuk menggredkan kematangan buah kelapa sawit, misalnya teknik pengimejan spektroskopi. Penyelidikan ini bertujuan untuk meningkatkan keberkesanan penderia kematangan buah kelapa sawit menggunakan aruhan resonans tiga gegelung teras udara jenis rata. Objektif kajian yang pertama adalah untuk merekabentuk penderia kematangan buah kelapa sawit tiga gegelung teras udara. Selain itu, tesis ini juga bermatlamat untuk mengkaji hubungan antara frekuensi resonans dan kemuatan sampel buah kelapa sawit terhadap minggu dan kandungan kelembapan buah. Tambahan pula, konfigurasi tiga siri dan tunggal gegelung teras udara jenis rata dibandingkan dari segi kepekaan dan kepersisan untuk memilih gegelung bersiri terbaik di antara dua jenis gegelung yang diuji. Kaedah yang digunakan dalam kajian ini untuk pengesanan kematangan buah adalah dengan menggunakan konsep penderia aruhan berdasarkan teknik frekuensi resonans. Melalui nilai frekuensi resonans, kemuatan buah dapat dikenalpasti dengan menolak kemuatan diri gegelung dengan sampel dan tanpa sampel. Terdapat tiga jenis penilaian digunakan dalam kajian ini, iaitu: perbandingan terus buah masak dan muda, mingguan dan kelembapan. Melalui ketiga-tiga penilaian ini, perbezaan antara buah masak dan muda dapat dikenalpasti dan dibandingkan. Prestasi kepekaan ditaksir menggunakan perbezaan nilai dan kepersisan pula ditaksir menggunakan pekali kelainan c_v. Berdasarkan keputusan yang diperoleh, puncak aruhan daripada lengkung aruhan-frekuensi beralih menghampiri lengkung puncak aruhan udara apakala buah kelapa sawit semakin matang, namun demikian kemuatan buah berkurangan apabila buah kelapa sawit semakin matang yang disebabkan oleh pengurangan kandungan lembapan dalam buah. Bergantung

kepada konfigurasi gegelung, teknik tiga gegelung bersiri dapat mempengaruhi hasil kepekaan berbanding struktur gegelung tunggal jenis rata. *Triple I* ialah tiga gegelung bersiri dengan jumlah lilitan tetap *N*=200 dengan panjang yang berbeza (3mm, 5mm, 10mm) telah menunjukkan keputusan yang baik berbanding gegelung *Triple II* dengan panjang tetap *l*=5mm dan bilangan lilitan yang berbeza (*N*=140, 200, 400). *Triple I* dan *II* juga telah meningkatkan prestasi kepekaan gegelung tunggal dengan perbezaan purata frekuensi resonans puncak pertama masing-masing meningkat sebanyak 353% dan 63%. Di samping itu, *Triple I* juga telah terbukti lebih persis dengan nilai pekali kelainan yang kecil untuk ketiga-tiga puncak (c_v = 0.2284) berbanding *Triple II* (c_v = 0.8401). Kesimpulannya, hasil penyelidikan penderia ini membuktikan keupayaan unsur aruhan, seperti gegelung, untuk digunakan sebagai elemen pengesanan untuk menentukan tahap kematangan buah kelapa sawit.

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

Norhisam bin Misron, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Ishak bin Aris, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Roslina binti Mohd. Sidek, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

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Name and Matric No.: Nor Aziana binti Aliteh, GS44943

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Signature: ______________________________
Name of Chairman of Supervisory Committee: Professor Dr. Norhisam bin Misron

Signature: ______________________________
Name of Member of Supervisory Committee: Professor Dr. Ishak bin Aris

Signature: ______________________________
Name of Member of Supervisory Committee: Associate Professor Dr. Roslina binti Mohd. Sidek

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LIST OF ABBREVIATIONS

FFB	Fresh Fruit Bunch
MPOB	Malaysian Palm Oil Board
RGB	Red Green Blue
NIR	Near Infrared
GANN	Genetic Algorithm Neural Network
MRI	Magnetic Resonance Imaging
NMR	Nuclear Magnetic Resonance
DLE	Delayed Light Emission
NIRS	Near-Infrared Spectrometry
ANN	Artificial Neural Network
MLR	Multiple Linear Regression
PLS	Partial Least Square
CIE	Commission Intl. de l'Eclairage
LED	Light Emitting Diode
UV	Ultra Violet
PSII	Photosystem II
3D	Three Dimension
CT	Computer Tomography
THz-TDS	Terahertz Time-Domain Spectrometry
DAP	Days After Pollination
HSI	Hue Saturation Intensity
VIS	Visible Spectrophotometry
FS-MLR	Forward-Stepwise Multiple Linear Regression
CMOS	Complementary Metal–Oxide–Semiconductor
BRR_FRF	Blue-to-Red Fluorescent Ratio
C&RT	Classification and Regression Tree
WAA	Week After Anthesis
ANOVA	Analysis of Variance
VNA	Vector Network Analysis
AC	Alternating Current
DC	Direct Current
SRF	Self-Resonance Frequency
ABS	Acrylonitrile Butadiene Styrene
RLC	Resistor Inductor Capacitor

LIST OF SYMBOLS

N	Number of turns
l	Coil core length
X	Reactance
Z	Impedance
C_S	Self-capacitance
C_{air}	Air coil self-capacitance
C_f	Fruitlet capacitance
f_R	Resonance frequency
L	Inductance
C	Capacitance
f_{SRF}	Self-resonance frequency
L_{max}	Maximum inductance
w	Coil core width
h	Coil core height
m_{before}	Mass before oven-drying
m_{after}	Mass after oven-drying
$L_{aircoil}$	Inductance of air coil
c_N	Nagaoka coefficient
L_0	Ideal inductor inductance
μ_0	Permeability in vacuum
D_0	Diameter of coil wire
k	Elliptic modulus
k'	Complementary elliptic modulus
E	Complete elliptic integral of the first type
K	Complete elliptic integral of the second type
θ	Angular coordinate
ε	Permittivity
ε_0	Permittivity of free space
ε_r	Relative permittivity of medium
x	Length of electric field line connecting two elementary surfaces
C_{ttc}	Insulating coating capacitance
C_{ttg}	Air gap capacitance
D_c	Diameter of coil wire conductor
C_{tt}	Total capacitance
L_s	Series inductance
C_R	Self-capacitance at resonance frequency
$\Delta\overline{f_R}$	Mean resonance frequency difference
$\Delta\overline{f_{Rr}}$	Mean ripe resonance frequency

$\Delta\overline{f_{Ru}}$	Mean unripe resonance frequency
Δf_R	Resonance frequency difference
$\Delta week$	Range of week
$\Delta moisture$	Range of moisture
α_{wf_R}	Resonance frequency at *Week*=0
β_{wf_R}	Sensitivity or gradient of resonance frequency against week
α_{mf_R}	Resonance frequency at *Moisture*=0
β_{mf_R}	Sensitivity or gradient of resonance frequency against moisture
$\Delta\overline{C_f}$	Mean fruitlet capacitance difference
$\Delta\overline{C_{fr}}$	Mean ripe fruitlet capacitance
$\Delta\overline{C_{fu}}$	Mean unripe fruitlet capacitance
ΔC_f	Fruitlet capacitance difference
α_{wC_f}	Fruitlet capacitance at *Week*=0
β_{wC_f}	Sensitivity or gradient of fruitlet capacitance against week
α_{mC_f}	Fruitlet capacitance at *Moisture*=0
β_{mC_f}	Sensitivity or gradient of fruitlet capacitance against moisture
c_v	Coefficient of variation
σ	Standard deviation
σ_c	Standard deviation for resonance frequency
σ_f	Standard deviation for fruitlet capacitance
$\bar{\Delta}$	Differences mean
$\bar{\Delta}f_R$	Resonance frequency differences mean
$\bar{\Delta}C_f$	Fruitlet capacitance differences mean
Nf_{rr}	Normalized resonant frequency of ripe samples
Nf_{ru}	Normalized resonant frequency for unripe samples
Nf_r	Normalized resonant frequency

CHAPTER 1

INTRODUCTION

1.1 Background

Year 2017 marks the 100-year anniversary for Malaysia's oil palm industry after Henri Fauconnier began to commercialize the oil palm plantation at Tennamaram Plantation, Selangor in 1917. Malaysia currently accounts for 39% of world palm oil production and 44% of world exports. Therefore, Malaysia has an important role as one of the biggest palm oil products producers and exporters in fulfilling the growing sustainable global needs for oils and fats [1]. Oil palm tree is well-known as one of the most efficient oilseed crop in the world. One hectare of oil palm plantation is able to harvest up to ten times more than the other oilseed crop [2]. The *Elaeis guineensis* is the most common species of oil palm in oil palm plantation due to its thick mesocarp and thin endocarp, making it suitable for commercialization [3]. Oil palm fresh fruit bunch (FFB) will undergo crude palm milling process to extract the palm oil as well as palm oil by-products. The standard procedure to grade the oil palm procedure is commonly done through visual inspection by human graders based on the oil palm grading manual published by Malaysian Palm Oil Board (MPOB). The ripeness of the oil palm FFB is identified primarily from the colour of the oil palm fruit exocarp as well as the number of loose fruit or empty socket of the bunch [4]. Furthermore, it is important to pluck the oil palm FFB at the optimal maturity stages in order to maximize the rate of extraction. Various methods for oil palm fruit maturity grading detection method have been introduced and the most popular method is spectroscopy method with RGB visual imaging techniques and software analysis [5-10]. Laser-based imaging ripeness detection method [11] have also been introduced as well as using fluorescent technique [12]. M. Saufi et al. [13] introduced oil palm fruit grading using Near Infrared (NIR) imaging and D. Silalahi et al. [14] presented Genetic Algorithm Neural Network (GANN) software to analyse NIR spectral data. In addition, S. Zolfagharnassab et al. [15] initiated a comparison using thermal sensor to detect changes in mean temperature as the oil palm FFB ripens. Moreover, S. Shaarani et al. [16] proposed oil palm fruit ripeness monitoring development with the use of magnetic resonance imaging (MRI) together with bulk nuclear magnetic resonance (NMR). Besides that, microwave moisture sensor was introduced for in-situ measurement of complex permittivity of moisture content using six and five-port reflectometer [17–19]. This study is a continuation from N. Hasmiza et al. that introduced a new inductive concept using circular coil [20], single flat-type air coil with various dimension [21] and dual resonance frequency effect [22]. This thesis aims to develop triple series flat-type air coil with triple resonance peak in order to increase the sensor's sensitivity and precision as compared to their matching single coil.

1.2 Problem Statement

Grading the oil palm fruit ripeness stages is one of the most frequently stated problems in the oil palm industry. The dependency on human grader to grade the maturity of the oil palm fresh fruit bunch has been a traditional way of determining the ripeness of the fruit [4]. Nevertheless, human graders are prone to errors when objectifying the ripeness of the fruit by looking at its skin colour and the number of fruitlets that are loose and have fallen onto the ground. The main challenge faced by researchers is to differentiate the oil palm FFB ripeness category so that the oil palm mill can maximize the extraction rate and speed up the grading process. Thus, this problem opens up another study area by using coil sensor to detect changes by utilizing the coil's resonance frequency as was done previously by N. Hasmiza et al. [20-22].

The previous study looked into the use of flat-type air coil and the coil dimension that showed the best results was obtained with coil wire 0.12mm and 5mm length [21]. A further study by the previous researcher found that the dual resonance capability produced better performance than the single coil by using two coils in series that produced dual peak resonance, with coil configuration 140-200 showing the best results [22]. Therefore, this thesis aims to investigate whether the triple series resonance can show better performance as compared to the single coil. Previous study also showed improvement for dual series coil with different number of turns [22], but in this study, the effect of both length and the number of turns in triple series are tested for their performances. Furthermore, the previous study also did not study fruit moisture content and self-capacitance evaluation. Hence, this thesis aims to investigate their relationship further with respect to the ripeness of the oil palm FFB and finally select the coil configuration that has the best potential in terms of sensitivity and precision.

1.3 Objectives

The objectives of this research are as follows:

1. To design and fabricate triple flat-type coil series configuration for oil palm fruit maturity sensor
2. To investigate the relationship between oil palm fruitlet sample resonance frequency and fruitlet capacitance against progressing week and moisture content.
3. To compare the performance between single and triple flat-type coil and to identify the best triple series flat-type air coil configuration among two types of coil series tested.

1.4 Thesis Contributions

The primary contribution of this thesis is the development sensitivity improvement of the inductive resonance coil sensor to differentiate the maturity stages of the oil palm FFB. This thesis compares triple flat-type and its respective single flat-type coil. Two types of triple flat-type air coil structure are designed and fabricated. Triple I has same number of turns N=200 but different length (10-5-3mm) and Triple II have same length l=5mm but different number of turns (400-200-140). The single flat-type is constructed and tested in order to replicate previous studies' findings and to compare its performance evaluation used in this study. Previously, the dual resonance frequency [22] comparison emphasised on different number of coil, which is replicated by Triple II configuration. The sensitivity of the inductive oil palm fruit sensor is observed with the analysis on triple resonant frequencies from three equivalent single flat-type air coil structure.

The development of this sensor verifies the improved capability of the inductive element as a detection element for determining the maturity stages of oil palm FFB. Furthermore, the relationship between the resonance frequency and its respective air coil self-capacitance with week and moisture content of the fruitlets were investigated and analysed in order to determine the best coil configuration for sensor application.

1.5 Scope of Work and Limitation

The triple flat-type air coil sensor are developed based on the best structure mentioned in the previous study basic structure and principle from single [21] and dual coil structure [22]. The proposed structure used in this study is fabricated with two types of coil configuration: single and triple series. The single air coil configuration is constructed based on the individual triple series in order to compare their performance. There are two types of triple flat-type series introduced namely Triple I and Triple II. Triple I consists of constant number of turns N while Triple II with constant air core length l. Both types require the peak to be within 10MHz due to the limitation of impedance analyser. The oil palm fruitlet samples species used for this experiment is *Elaeis guineensis* with commercial *Tenera* cultivar. The fruitlet samples are tested weekly and its moisture content is measured. All the experiments are conducted at room temperature (25°C), where the permittivity and permeability of air is assumed to be constant in laboratory condition.

1.6 Thesis Outline

The outline of each chapter is described as follows:

Chapter One provides research overview that includes background, problem statement, objectives, thesis contribution, scope of work and limitation. The background introduces briefly regarding the oil palm industry in Malaysia and the current research related to the oil palm ripeness grading method and technology. The problem statement in this thesis emphasises on the research motivation and thesis objectives. The scope of work briefly introduces the type of sensor structure used and the research limitation.

Chapter Two reviews about general non-destructive techniques for fruit quality analysis which involves spectroscopy analysis, mechanical characteristic analysis, and miscellaneous methods used other than the mentioned analyses. The next section consists of oil palm fruit related topic, such as its botany, chemistry of oil palm fruit, and the grading guidelines by MPOB. The overview of related research from various study are reviewed and summarised. Moreover, the last section of the chapter talks about the air coils inductor behaviour at high frequency and its self-resonance frequency. Lastly, the sensor characteristics are briefly explained for accuracy, sensitivity, and precision.

Chapter Three contains methodology description used throughout this research. Basic concept detection and design process consideration are also explained. The next section discusses about data collection methods that includes sample selection, weekly field experiment, and moisture content determination using oven-drying method. The following section describes the single and triple flat-type air coil structure that comprises of its basic structure, electrical diagram, and experiment setup. Then the basic mathematical estimation for inductance and self-capacitance are briefly introduced. Experiment results analysis section involving peak resonance frequency, self-capacitance, and fruitlet capacitance along with comparison parameter analysis are also explained.

Chapter Four comprises of result analysis and discussions. The chapter begins with weekly oil palm FFB sample timeline, FFB moisture content against week and sample data selection. The coil characteristics are further examined with the value of measured inductance at 100Hz and air coil characteristics for both triple and single coil. The subsequent section consists of result analysis for single and triple flat-type air coil inductance-frequency graph characteristic, peak resonance frequency, and fruitlet capacitance. The triple and single coils are compared for peak resonance frequency and fruitlet capacitance difference to evaluate sensitivity and coefficient of variation comparison to evaluate precision. Finally, a benchmarking section is added to compare the previous design and the triple flat-type air coil performance.

Chapter Five presents the conclusions to sum up the findings obtained through this study. Additionally, this chapter also contains suggestion and recommendation for future study in this research.

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