UNIVERSITI PUTRA MALAYSIA

ENERGY HARVESTING SYSTEM FOR KENAF FIBRE REINFORCED EPOXY COMPOSITE VERTICAL WIND TURBINE BLADE

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By

AHMAD HAMDAN BIN ARIFFIN

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

December 2015

DEDICATION

To my parents, Ariffin Said and Naimah Abdul Aziz, for their unconditional love, understanding and moral support.

To my beloved wife Fadzillah Mahmad and children Ahmad Faiz, Ahmad Fahmi and Aisyah Solehah for their motivation.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

ENERGY HARVESTING SYSTEM FOR KENAF FIBRE REINFORCED EPOXY COMPOSITE VERTICAL WIND TURBINE BLADE

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Chair : Faizal Mustapha, PhD, PEng
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The usage of wind energy as a form of renewable energy is becoming increasingly popular year by year. The performance of wind turbine systems depends upon factors such as design, aerodynamic performance and material selection. Thus, Structural Health Monitoring (SHM) has become crucial in evaluating the performance of wind turbines in real time. Furthermore, the application of smart material in SHM systems can be utilised as a micro energy harvester as well. Nonetheless, the application of SHM in Malaysia's climate for wind turbines is still premature, especially in the use of biocomposite material in its blade system. Hence, the objectives of this research can be summarised as follows: to assess the the effect of bonding technique of Macro Fiber Composite (MFC) system in a kenaf composite fibre and incorporated for micro energy harvester in wind turbine blade. A feasibility investigation of bonding MFC techniques and fabrication process optimisation were conducted. The mechanical properties of woven and random chopped kenaf were investigated, especially with regards to flexural and tensile strength. A modal testing experiment was conducted on the kenaf plate to assess the correlation factors involved in the vibrating structure, including natural frequency. A plate vibration test was performed on the kenaf plate to analyse the factors influencing the performance of the micro energy harvester. A thorough analysis of the bonding MFC technique was also performed on the kenaf composite turbine blade. The experiment was conducted on a tested laboratory vertical axis wind turbine for micro energy harvesting. Further statistical analysis via the Taguchi method was applied on the plate and the turbine blade. It was found that the embedded MFC was capable of inducing electricity and a signal. In mechanical properties analysis, the properties of woven kenaf composite improved up to 199% and 177%, as compared to random chopped kenaf, for flexural strength and tensile strength respectively. The bonding type and resonance of particular structure factors show significant influence on the performance of the micro energy harvester via Taguchi analysis in plate vibration test. Bonded MFC on the surface shows a 348% increment compared to embedded MFC in turbine blade micro energy harvesting analysis. Projection performance of functional VAWT shows that additional percentage, from 26% up to 107%, energy harvested from the wind turbine system for bonded MFC. Finally, energy harvested kenaf composite turbine blade was developed successfully.

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

SISTEM PENGHASILAN TENAGA UNTUK BILAH KINCIR ANGIN MENEGAK

Oleh

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Penggunaan tenaga angin sebagai sumber tenaga boleh diperbaharui semakin meningkat tahun demi tahun. Prestasi dan kualiti system kincir angin bergantung kepada beberapa factor seperti rekabentuk, prestasi aerodinamik dan pemilihan bahan. Sehubungan dengan itu, sistem pantauan kesihatan struktur (SHM) menjadi sangat penting bagi mengukur prestasi kincir angin secara terus menerus. Tambahan pula, aplikasi bahan pintar dalam sistem SHM boleh juga digunakan sebagi penghasil tenaga mikro. Walau bagaimanapun, aplikasi SHM dalam cuaca di Malaysia untuk penggunaan kincir angin masih lagi baru. Terutamanya, pendekatan bio komposit pada penghasilan bila kincir angin. Oleh yang demikian, objektif kajian meliputi perkara berkaitan untuk mengukur kesan kaedah tampalan *Macro Fiber Composite* (MFC) dalam komposit kenaf dan integritnya sebagai penghasilan tenaga mikro dalam bilah kincir angin.. Ujian keboleh aplikasi kaedah tampalan MFC dan perbandingan kaedah pembuatan dilaksanakan dalam kajian. Ujian mekanikal bahan untuk kenaf kasar dan kenaf tenunan dilaksanakan dengan mendalam pada aspek kekuatan kelenturan dan kekuatan ketegangan. Ujian *Modal* turut dilakukan bagi melihat kaitan antara faktor-faktor yang terlibat pada struktur bergetar. Ujian plat getaran dilakukan pada plat kenaf untuk menganalisa faktor yang mempengaruhi prestasi penghasilan tenaga mikro. Setelah itu, analisa ke atas kaedah tampalan MFC dilaksanakan pada bilah kincir angin kenaf. Ujian ini dilaksanakan pada prototaip kincir angin berpaksi menegak untuk menganalisa kualiti penghasilan tenaga mikro dan SHM. Kaedah statistik Taguchi juga digunakan pada ujian plat dan bilah kincir angin. Kajian menunjukkan kaedah implan MFC mampu menghasil tenaga elektrik dan memancarkan isyarat. Ujian ciri mekanikal bahan menunjukkan kenaf tenun lebih baik berbanding kenaf kasar sehingga 199% dan 177% pada aspek kekuatan kelenturan dan kekuatan ketegangan. Faktor kaedah tampalan MFC dan resonan struktur tertentu menunjukkan kesan yang besar kepada prestasi penghasilan tenaga mikro hasil analisa menggunakan Kaedah Taguchi dalam ujian getaran plat. Tampalan MFC di permukaan menunjukkan peningkatan sebanyak 348% jika dibandingkan kaedah implan di dalam ujian analisa penghasilan tenaga di bilah kincir angin. Unjuran prestasi sistem kincir angin menegak menunjukkan pertambahan 26% hingga 107% penghasilan tenaga dengan menggunakan kaedah tampalan di permukaan untuk sistem kincir angin. Akhirnya, bilah kincir angin komposit kenaf untuk janaan tenaga berjaya dibangunkan

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I certify that a Thesis Examination Committee has met on, 30 December 2015 to conduct the final examination of Ahmad Hamdan bin Ariffin on his thesis entitled "Energy harvesting system for kenaf fibre reinforced epoxy composite vertical wind turbine blade" 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 candidate be awarded the Doctor of Phillosophy.

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LIST OF ABBREVIATIONS

ABA	Amplitude Based Assessment
CFRP	Carbon fibre reinforced plastic
C_p	Power coefficient
CSI	Condition Structural Index
DF	Degree of freedom
FFT	Fast Fourier Transform
FRF	Frequency Response Functions
FRP	Fibre-reinforced plastics
H/D	Height-to-diameter
HAWT	Horizontal Axis Wind Turbine
IPV	Inner product vector
MFC	Macro Fiber Composite
MLP	Multi-layer perceptron
MW	Megawatt
OA	Outlier analysis
PAGV	Power-augmentation-guidevane
PCA	Principle component analysis
PVDF	piezoelectric polymer polyvinylidene fluoride
PZT	Lead Zirconate titanate
QP	Bimorph Quick Pack
RE	Renewable energy
SHM	Structural Health Monitoring
TSR	Tip speed ratio
UAV	Unmanned aerial vehicle
VAWT	Vertical Axis Wind Turbine
VGOT	Variable geometry oval trajectory

CHAPTER 1

INTRODUCTION

1.1. Background

The demand for wind energy applications in Malaysia will continue to increase as fossil fuel prices continue to increase and the reservoir keeps decreasing. For wind energy, wind turbine applications should be properly selected. This technology is applied widely in several regions of the world and it already has mature technology, a good infrastructure and relative cost competitiveness (Ciang et al., 2008). In this field, wind turbines can be categorised into two main types depending on the axial direction of the rotor shaft: the first one is the Horizontal Axis Wind Turbine (HAWT) and the second is the Vertical Axis Wind Turbine (VAWT). The HAWT has blades mounted radially from the rotor. Modern types usually have two or three blades and are generally used for large scale, grid connected electrical power generation. The VAWT is not as common and has only recently been used for large scale electricity generation. Several studies have shown that the application of the VAWT offers more advantages compared to the HAWT. The VAWT does not have to be orientated to the wind direction. Besides this, it does not need a tower, hence reducing the capital cost. In fact, the generator is mounted at ground level for easy access (Kanellos and Hatziargyriou, 2008, Yeh and Wang, 2008, Ibrahim, 2009).

The weather and climate in Malaysia could give an advantage to the VAWT compared to the HAWT as discussed in the literature review. In order to monitor the sustainability of each component in the VAWT, a proper method should be used to monitor the turbine blade and the overall system before the operation as well as during the operation of the VAWT. In this situation, the application of Structural Health Monitoring (SHM) is crucial. SHM is a method that aims to identify the health of an engineered system throughout its lifecycle (Adams et al., 2011). By using SHM, design rotors and drive trains can be reassessed and replaced with automatic state awareness and control measures to reduce the overall weight. Furthermore, manufacturers could use health information about loads and the damage correlated with these loads to improve wind turbine designs, manufacturing and quality control processes, and shipping and installation methods (Ciang et al., 2008). There are several methods for detecting damage or failure in the blade structure. The methods include Acoustic Emission, Ultrasonics, Fibre Optics, the Laser Doppler Vibrometer and Thermal Imaging (Rumsey and Paquette, 2008, Ciang et al., 2008, Ghoshal et al., 2000, Marquez et al., 2012, Mohd Aris et al., 2012). In addition, Macro Fiber Composite (MFC) and piezoelectric smart material offer better technology, which not only detect damage but act as an electricity harvesting mechanism as well (Anton and Sodano, 2007, Liu et al., 2012). In this system, the sensor will react if several situations occur, such as the curvature of the structure, a strain state in the sensors, damage in the structure and the failure mode of the structure by buckling (Sundaresan et al., 1999). The sensors act as well as SHM as they offer certain advantages, e.g. compactness, lightweight, low-power consumption, repeatable inputs for active-sensing approaches, ease of activation through electrical signals, low cost compared to other devices and easy installation (Sundaresan and Schulz, 2006, Eloi Figueiredo Gyuhae Park et al., 2012). The application of piezoelectric material as an enhancement of the VAWT in terms of energy harvesting could become a new challenge. Consequently, as the

VAWT plays a major role as the main energy collector, piezoelectric material can act as a micro energy harvester or wind vibration energy harvester (Liu et al., 2012).

On the other hand, the fabrication of turbine blades has become an important issue as well. Composite materials have started to replace the applications of metal. Glass fibres are the most widely used material to reinforce plastics due to their low cost and fairly good mechanical properties. The use of natural plant fibres as a reinforcement in fibre-reinforced plastics (FRP) to replace synthetic fibres such as glass is receiving attention, because of its advantages, such as renewability, low density, environmental waste management and high specific strength. Recent studies have investigated the development of biocomposite materials using natural fibres such as flax (Stuart et al., 2006, Oksman et al., 2003), bamboo (Lee and Wang, 2006), pineapple (Liu et al., 2005), jute (Plackett et al., 2003), kenaf (Nishino et al., 2003, Cao et al., 2007) as a reinforcement for biodegradable plastics. These studies have examined the moulding conditions, the mechanical properties, and interfacial bonding (Ochi, 2008) and show positive results. In Malaysia, kenaf has become the future commodity for economic development. Lembaga Kenaf dan Tembakau Negara have been appointed to ensure that the kenaf industry grows significantly in Malaysia. Furthermore, the research on kenaf as an alternative in the automotive industry is convincing and is showing huge potential (Davoodi et al., 2008). Interestingly, kenaf has already undergone extensive investigations leading to significant findings (Davoodi et al., 2010, Zampaloni et al., 2007, Akil et al., 2011). However, this practice has still not been applied in turbine blade fabrication.

Hence, this research will focus on optimising the application of kenaf in turbine blade fabrication, the bonding technique of MFC in kenaf turbine blades and the micro energy harvested from the MFC. Finally, a prototype of a Malaysian-made biocomposite turbine blade with a smart embedded SHM system can be produced for the benefit of future generations. The technology will also be equipped with a smart SHM sensor for better monitoring and maintenance work schedules.

1.2. Problem Statement

The discussion of the design and aerodynamics of VAWTs has almost matured. The technology is already established and there are various types of VAWT commercially available in the market. However, two issues can be highlighted in terms of green technology. Firstly, there is the consideration of the application of natural fibres or green material in order to avoid and reduce the utilisation of synthetic composite. Serious investigations on application of natural fibre in wind turbine blade fabrication need to be conducted. Additionally, there is still a gap in optimising the yarn size selection, yarn weave orientation, the stacked layer orientation and the fabrication process of natural fibres especially in fabricating VAWTs. Kenaf was selected in this study as it is one of the important commodity sources in Malaysia. Hence, mechanical properties and natural frequency of kenaf fibre composite need to be further investigated.

Secondly, there is the issue of the enhancement of smart material in SHM technology which performs as a micro energy harvester. MFC is smart material which can perform as a sensor, actuator and energy harvester. The utilisation of this technology could bring VAWTs a step forward with regards to additional features. However, it needs further analysis and optimisation in terms of the dual function of the MFC. Several issues can be highlighted here such as the production of efficient electronic circuitry for energy harvesters, optimising VAWT material, optimising material for both SHM and micro energy harvesters, the MFC bonding method and the critical location in VAWTs for optimum signal receivers.

Furthermore, the utilisation of MFC for self-energised devices could bring VAWTs a step forward concerning additional features. The state of the problem can be illustrated as follows:

1. Can MFC transmit signals and induce energy when bonded or embedded in biocomposite material?
2. Does kenaf fibre perform better in terms of its mechanical properties compared to the existing findings?
3. What is the best orientation for kenaf fibre in order to produce better mechanical properties in terms of flexural and tensile strength?
4. What factors influence the performance of micro energy harvesters?
5. What is the cut in the velocity of the VAWT system that will be developed?

All of these issues are being investigated in this thesis. Several experimental methodologies are employed to achieve the research objectives. Flexural and tensile tests are utilised to determine the mechanical properties, and microstructure analysis is conducted via a scanning electron microscope (SEM). The vibration test, modal testing analysis and energy harvesting tests are performed to analyse the effect of the MFC bonding technique and the kenaf woven type application. Lastly, the concept is applied on a prototype of a wind turbine for the laboratory tests. Knowledge of wind turbine design and fabrication is synthesised as well throughout the research activities.

Ultimately, this research is targeted to enhance the usage of natural fibre in VAWT applications equipped with a micro energy harvester. It specifically concentrates on the MFC bonding technique, the natural fibre orientation and the layer orientation in promoting the micro energy harvester application.

1.3. Research Objectives

There are four main objectives in this study, namely:

1. To assess the effect of a bonding technique of Macro Fiber Composite (MFC) system in kenaf fibre reinforced epoxy composite for micro energy harvesting.
2. To evaluate the mechanical properties of woven kenaf composite at different yarn fibre orientation and stacked layer orientation and random chopped kenaf composite.
3. To establish the correlation among the factors influencing the performance of smart kenaf fibre reinforced epoxy composite plate at different vibration frequencies for micro energy harvesting.
4. To incorporate smart micro energy harvester in kenaf fibre reinforced epoxy turbine blade for VAWTs for the climate of peninsular Malaysia.

1.4. Scope of the study

The scope of this research concerns the application of kenaf fibre, MFC and a micro energy harvesting system for VAWTs. The micro energy harvested from the vibration of kenaf composites turbine blade is expecting to store in a rechargeable battery and become lifelong battery. The factors involved affecting the harvesting performance is investigated in this research.

The mechanical properties of woven and random chopped kenaf composite are determined. The tensile, flexural test and SEM analysis are conducted to compare the mechanical properties of woven and random chopped kenaf composite as well as the fibre and stacked layer orientation of woven kenaf composite. Mechanical properties testing was conducted to experimentally select the best sample for this research. No extensive research study conducted at various aspects on the fibre orientation especially for mechanical properties analysis. Furthermore, the fibre orientation is focus on 0° and 90° fibre orientation as the MFC is optimally responded to contract and tensile deformation.

Furthermore, optimisation of the factors is performed, including embedding MFC in the kenaf composite, and bonding MFC on the surface of the kenaf composite (woven and unwoven kenaf composite). Modal testing, vibration testing and micro energy harvester testing are conducted on kenaf plates and the kenaf turbine blade to determine the effect of the factors on the micro energy harvesters. Statistical analysis via the Taguchi method and Analysis of Variance (ANOVA) are conducted on the experimental findings to optimise the parameters and evaluate the factors influencing micro energy harvester performance. These analyses are utilised to synthesise the correlation among the mechanical properties, the factors influencing micro energy harvester performance and the vibration on the VAWT system to enhance the application of the micro energy harvester system

Even though the main research is focused on the micro energy harvesters, a fundamental assessment of structural health monitoring testing on turbine blades is performed as well, to compliment the research for future reference and benefit. The frequency response function graph is observed and compared between normal and damaged turbine blades for both bonded and embedded MFC.

A working prototype of a VAWT is designed, fabricated and tested. A VAWT is fabricated to provide the real platform for the micro energy harvester application. No extensive research to optimise the VAWT design. Hence, the fabrication process is reported as engineering knowledge growth to the author and is out of the research scope.

1.5. Organisation of the thesis

This thesis, consisting of five chapters, is traditionally organised to provide the background, the literature review, the experimentation method and its subsequent analysis and conclusions. The details of the chapters are summarised as follows:

Chapter 1 introduces the background and motivation for the study as well as outlining the scope and objectives of the research.

Chapter 2 summarises the literature review which will explain the fundamentals of VAWTs, the manufacturing process of kenaf composite and MFC as a sensor and a micro energy harvester. The chapter will also describe the potential of MFC in the kenaf wind turbine blade of the VAWT.

Chapter 3 describes the experimental methods including the experimental techniques, materials and apparatus used. Besides this, detail explanation of the fabrication process used in this research. It includes the weaving machine design, the weave process, mould fabrication and wind turbine system assembly.

Chapter 4 reports the results and findings obtained from the experiments. The mechanical properties of the kenaf composite are depicted and a SEM is used to determine the bonding mechanical failure of the kenaf composite. Analysis of vibration and modal testing on the kenaf plate and turbine blade composite are reported. The wind turbine performance report from the wind tunnel is presented in this chapter. Statistical analysis on modal analysis and vibration analysis are shown to correlate the natural frequencies and mechanical properties of the structure.

Chapter 5 summarises the research work, providing several conclusions and recommendations. Further developments are also considered.

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LIST OF PUBLICATIONS

Journal papers

1. A.Hamdan, F. Mustapha, K.A. Ahmad, A. S. Mohd Rafie , A review on the micro energy harvester in Structural Health Monitoring (SHM) of biocomposite material in Vertical Axis Wind Turbine (VAWT) system; A Malaysia perspective, Journal: Renewable & Sustainable Energy Reviews, (2014) 35, pages 23-30 (ISI Journal, impact factor =5.51)

2. A.Hamdan,F. Mustapha, K.A. Ahmad, A. S. Mohd Rafie, Mohamed Thariq Hameed Sultan, M.R. Ishak A review on the self energize Structural Health Monitoring (SHM) in Vertical Axis Wind Turbine (VAWT) system, Applied Mechanics and Materials (2014) 564, pages 157-163. (SCOPUS)

3. Ahmad Hamdan Ariffin, F. Mustapha, Ahmad Nizam Jamaludin, Mohd Faruq Abdul Latif, Optimization of accelerated ducted design in wind turbinesystem using Computational Fluid Dynamics (CFD). Published is Australian Journal of Basic and Applied Sciences 8(15): 264- 268, 2014

4. A.Hamdan, F. Mustapha, K.A. Ahmad, A. S. Mohd Rafie, M.R. Ishak, A.E Ismail, The bonded macro fiber composite (MFC) and woven kenaf effect analyses on the micro energy harvester performance of kenaf plate using modal testing and Taguchi method . Accepted on *12 November 2015 in* Journal of Vibroengineering (ISI journal, impact factor=0.617)

5. A.Hamdan, F. Mustapha, K.A. Ahmad, A. S. Mohd Rafie, M.R. Ishak, A.E Ismail, The effect of customized woven and stacked layer orientation on tensile and flexural properties of woven kenaf fibre reinforced epoxy composites. International Journal of Polymer Science. (ISI journal, impact factor=1.195)-2 Oct 2015

Journal paper submitted

1. A.Hamdan, F. Mustapha, K.A. Ahmad, A. S. Mohd Rafie, M.R. Ishak, A.E Ismail, The Macro Fiber Composite (MFC) bonded effect analysis on the micro energy harvester performance and Structural Health Monitoring system of woven kenaf turbine blade for Vertical Axis Wind Turbine Application. Submitted to Journal of Wind Engineering and Industrial Aerodynamics (ISI journal, Impact factor= 1.414)-2 Dec 2015

Conference proceedings

1. A.Hamdan,F. Mustapha, K.A. Ahmad,A. S. Mohd Rafie, A review on material selection and manufacturing processes of Vertical Axis Wind Turbine (VAWT) blade, Proceedings of the 1st KAA Postgraduate Seminar (2014)
2. A.Hamdan, F. Mustapha, K.A. Ahmad,A. S. Mohd Rafie, M.R.Ishak, A.E Ismail, The effect of MFC bonded technique on the micro voltage harvester performance of a Kenaf fiber plate, 2nd International Conference on Advances in Structural Health Management and Composite Structures (ASHMCS2014), Republic of Korea. status: Accepted for presentation (2014)
3. Ahmad Hamdan Ariffin, F. Mustapha, Ahmad Nizam Jamaludin, Accelerated ducted design enhancement in wind turbine system via TRIZ concept solution. Proceeding in Malaysia Science Technology Conference 2015

Book

1. F. Mustapha, K.M.A Dahri, N. Al-Adnani, H. Ahmad Book: Innovation in Smart Material and structural Health Monitoring for Composite Application, Millersville, PA, Materials research Forum LLC, April 2016

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