UNIVERSITI PUTRA MALAYSIA

NUMERICAL INVESTIGATION OF KINGFISHER’S WING UNDER MULTI-PHASE FLIGHT FOR MICRO-AERIAL-VEHICLE

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By

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NUMERICAL INVESTIGATION OF KINGFISHER'S WING UNDER MULTI-PHASE FLIGHT FOR MICRO-AERIAL-VEHICLE

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August 2019

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Realizing an all-weather Micro-Aerial-Vehicle (MAV) has been this research's ultimate purpose. This research focuses on the originality of Kingfisher-inspired rigid and flexible wing designs and flapping patterns, and the novelty of multi-phase flapping flight. Numerical investigations have been conducted at 4.4 m/s, 6.6 m/s, and 8.8 m/s flight velocities, 11 Hz, 16 Hz, and 21 Hz flapping frequencies, and before, during, and after multi-phase impact with rain environment flight conditions. An experimental validation has been conducted using 3-D printed wing model under Particle Image Velocimetry (PIV) examination. The numerical investigations have been designed, mesh-constructed, and simulated using SolidWorks, Pointwise, and ANSYS Fluent software, respectively. For the main Kingfisher-inspired flapping rigid wing model, both coefficient of lift (C_L) and thrust force values under normal (ambient air) environment decreases with increased in flight velocity but increases with increased in flapping frequency, in a similar fashion. The main flapping rigid wing model at flight condition of 4.4 m/s flight velocity, 21 Hz flapping frequency, and 12° angle-of-attack shows the most optimal flight performance with exceptional overall aerodynamic characteristics. The flapping flexible wing model's resulted C_L value is 12.573% higher than the flapping rigid wing model under Single-phase flight condition. Furthermore, the flapping flexible wing model generates a staggering 81.064% higher thrust force with 41.030% lower coefficient of pressure (C_P) value than the flapping rigid wing model under the same flight condition. Under Multi-phase flight condition through simulated rain environment, the flapping flexible wing produces 14.726% higher C_L value and generates a staggering 82.527% higher thrust force with 62.770% lower C_P value than the flapping rigid wing at point of rain impact. This in turn enables the flapping flexible wing to adapt to the new simulated rain environment 24 times faster than the flapping rigid wing, which only took 0.0048 second. After rain impact, the flapping flexible wing produces 15.406% higher C_L value and generates a staggering 83.516% higher thrust force with 34.555% lower C_P value than the flapping rigid wing under said simulated rain environment. As a conclusion, the flexible wing model counterpart shows greater aerodynamic performance under every investigated flight conditions as compared to the rigid wing model.

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

KAJIAN NUMERIKAL SAYAP BURUNG RAJA UDANG DI BAWAH PENGARUH PENERBANGAN PELBAGAI FASA UNTUK KENDERAAN-UDARA-MIKRO

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Merealisasikan Kenderaan-Udara-Mikro (MAV) pelbagai cuaca telah menjadi tujuan utama penyelidikan ini dijalankan. Kajian ini memberi tumpuan kepada keaslian reka bentuk sayap tegar dan fleksibel yang diilhamkan oleh Kingfisher berserta corak mengepak, dan juga kebaharuan penerbangan pelbagai fasa. Penyiasatan berangka telah dijalankan pada kelajuan 4.4 m / s, 6.6 m / s, dan 8.8 m / s halaju penerbangan, 11 Hz, 16 Hz, dan 21 Hz frekuensi mengepak, dan ketika penerbangan sebelum, semasa, dan selepas kesan pelbagai fasa dengan persekitaran hujan. Pengesahan eksperimen telah dijalankan menggunakan model sayap bercetak 3-D di bawah pemeriksaan *Particle Image Velocimetry* (PIV). Penyiasatan berangka telah direka, dibina dengan mesh, dan disimulasikan menggunakan perisian SolidWorks, Pointwise, dan ANSYS Fluent. Bagi model sayap tegar yang menjadi kajian utama, kedua-dua pekali daya angkat (C_L) dan nilai daya teras di bawah persekitaran biasa (udara ambien) berkurang dengan peningkatan dalam halaju penerbangan tetapi meningkat dengan peningkatan dalam frekuensi mengepak. Model sayap tegar pada keadaan penerbangan kelajuan penerbangan 4.4 m/s, frekuensi mengepak 21 Hz, dan sudut serangan 12° menunjukkan prestasi penerbangan yang paling optimum dengan ciri-ciri aerodinamik yang hebat. Bagi kajian parametrik mengenai model sayap fleksibel dan keadaan penerbangan pelbagai fasa, model sayap fleksibel menunjukkan prestasi aerodinamik yang lebih baik sebelum impak hujan, pada titik impak hujan, dan penerbangan dalam persekitaran simulasi hujan selepas impak berbanding model sayap tegar. Model sayap fleksibel menghasilkan 12.573% lebih tinggi nilai C_L berbanding model sayap tegar dalam keadaan penerbangan satu fasa. Selain itu, model sayap fleksibel mampu menjana 81.064% lebih tinggi daya teras dengan 41.030% lebih rendah nilai pekali tekanan (C_P) berbanding model sayap tegar dalam keadaan penerbangan yang sama. Di bawah keadaan penerbangan pelbagai fasa menembusi persekitaran simulasi hujan, model sayap fleksibel yang menghasilkan 14.726% lebih tinggi nilai C_L dan 82,527% lebih tinggi daya teras dengan 62.770% lebih rendah nilai C_P berbanding model sayap tegar pada titik impak hujan. Ini seterusnya membolehkan model sayap fleksibel menyesuaikan diri dengan persekitaran simulasi hujan 24 kali lebih cepat daripada model sayap tegar, yang mengambil masa hanya 0.0048 saat. Selepas impak hujan, model sayap fleksibel menghasilkan 15.406% lebih tinggi nilai C_L dan menjana 83.516% lebih tinggi daya teras dengan 34.555% lebih rendah nilai C_P berbanding model sayap tegar dalam persekitaran simulasi hujan. Sebagai kesimpulan, model sayap fleksibel menunjukkan prestasi aerodinamik yang lebih baik di bawah setiap keadaan penerbangan yang disiasat berbanding dengan model sayap tegar.

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LIST OF ABBREVIATIONS

3-D	Three Dimensional
UAV	Unmanned-Aerial-Vehicle
MAV	Micro-Aerial-Vehicle
PAV	Pico-Aerial-Vehicle
DOF	Degree of Freedom
AOA	Angle of Attack
LEV	Leading Edge Vortices
CFD	Computational Fluid Dynamics
URANS	Unsteady Reynolds-Averaged Navier-Stokes
BSL	Menter's Baseline
ALE	Arbitrary Lagrangian–Eulerian
GCL	Geometric Conservation Law
SA	Spalart-Allmaras
MUSCL	Monotone Upstream-Centered Schemes for Conservation Laws
LRN	Low Reynolds Number
FVM	Finite Volume Method
PCG	Preconditioned Conjugate Gradient
SIMPLE	Semi-Implicit Method for Pressure Linked Equations
NURBS	Non-Uniform Rational B-Splines
SUPG	Streamline-Upwind Petrov/ Galerkin
PSPG	Pressure-Stabilized Petrov/ Galerkin
L-BFGS	Limited memory-Broyden-Fletcher-Goldfarb-Shanno
PDE	Partial Differential Equation

MST	Modified Strip Theory
PRESTO	Pressure Staggering Option
PISO	Pressure Implicit And Splitting Of Operators
FEM	Finite-Element Method
SMAC	Simplified Marker And Cell
OSCAB	Flapping-wing Concept Simulation Tool
UDF	User Define Function
ABS	Acrylonitrile Butadiene Styrene
RPM	Revolution-Per-Minute
PIV	Particle Image Velocimetry

LIST OF SYMBOLS

E	Young's Modulus
AR	Aspect Ratio
Re	Reynolds Number
k	Reduced Frequency
St	Strouhal Number
ρ	Density
γ	Diffusion coefficient
t	Time
x	Coordinate x
y	Coordinate y
z	Coordinate z
u	Velocity at x-axis
v	Velocity at y-axis
w	Velocity at z-axis
p	Pressure
q	Heat flux
τ	Stress
Pr	Prandtl Number
$\vec{u}$	Flow velocity vector
$\vec{u}_g$	Mesh velocity of moving mesh
b	Span-wise length
c_{root}	Root chord-wise length
c_{tip}	Tip chord-wise length
t_{root}	Root thickness
t_{tip}	Tip thickness

α	Angle-of-attack
h	Flapping amplitude
f	Flapping frequency
U_∞	Air flow velocity
U_{ref}	Reference velocity
L_{ref}	Reference length
ω	Angular frequency
φ	Phase angle
ϕ	Positional angle
θ	Elevation angle

CHAPTER 1

INTRODUCTION

1.1 Overview

In this chapter, the introduction to this numerical-focused research on Kingfisher-inspired flapping wing simulation will be discussed. This introductory chapter will cover on the history of the Micro-Aerial-Vehicle (MAV) research and production, the concept behind flapping wing MAVs, numerical importance of the flapping wing MAVs' design, problem statement, contribution of this research with objective and scope included, and this research's thesis outline at the end of the chapter.

1.2 Timeline of MAVs

For the past several decades, demands on smaller unmanned-aerial-vehicles (UAVs) are increasing. Reducing the size of a UAV will set new challenges as smaller size is as equivalent as smaller wingspan, and thus for flapping wing UAVs, smaller lift and thrust force values will be generated from a single flapping cycle. Therefore, smaller UAVs will have to face complex air flow characteristics, such as wake capture, due to flight conditions bounded within the low Reynolds number regime(Re<15000). Small UAVs are then coined in with the term micro-aerial-vehicles (MAVs). The utility of a MAV is vast; reconnaissance, search-and-rescue, terrain mapping, and military uses.

The high demands for such improvements have made researchers sought to nature's best fliers, ranging from small birds to small insects, for example, a typical house/fruit fly. The research trend started with the initial idea of how birds, or scientifically referred as ornithopters, fly with superb efficiency and how its wing mechanism affects its ability to maintain aerodynamic superiority and gain air dominance. Early works on fluid flow, its behavior, and active flow control have been summarized in a comprehensive review by Collis et al.[1] regarding the theory and how to effectively control the predicted fluid flow, and the issues arises from numerical and experimental approaches on active flow control.

During the last 5 years, several researches on ornithopter-type MAV development have been reported. Initial research was developing from experimental and numerical approaches of 2D flapping airfoils. As the research grow deeper, the need for a 3D flapping wing modelling and simulation arises for a more accurate performance-based predictions, despite cost factors. There are a vast amount of variables to consider in the attempt to optimize a flapping wing configuration, such as endurance and optimum aerodynamic capabilities. Strang studied the flapping flight of pterosaurs and analyzed its flapping flight efficiency[2]. Jackowski then published a guideline regarding the design and construction of an unmanned ornithopter, displaying specific variable considerations in optimizing flapping wing efficiency[3]. Bunget observed an alternative in increasing such efficiency by adopting a bat's flapping wing mechanism and created a bio-inspired MAV which is then termed BATMAV[4]. The ability of a bat to hover in mid-air is due to its unique flapping pattern of its wings, in which the wings produces positive lift during down-stroke and up-stroke as well, with efficient pitch control.

Till today, research on ornithopters is still on the fast track, though there are significant reduction in literature since insect-inspired MAV became the next new lead in MAV development. Grauer et al.[5] argued that flapping wing MAV researches using insect modelling have overshadowed those using ornithopter modelling due to abundance of insect aerodynamics data. Most of the insect models utilized rigid wing over flexible wing and calculations regarding aerodynamic loads are simply done in quasi-steady sense. He also did a study of a flapping wing ornithopter in the aspect of inertial measurements obtained from the ornithopter's flight data[6].

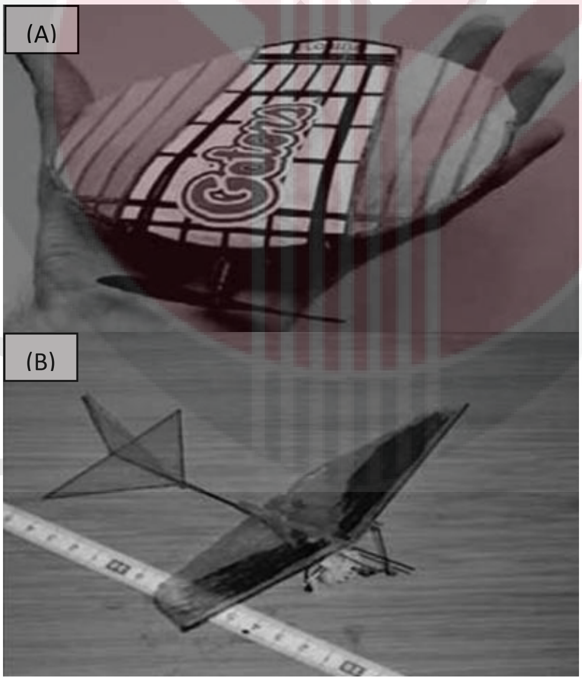

Figure 1.1: Types of Micro-Aerial-Vehicle (MAV); (A) rigid wing MAV[7] and (B) flapping wing MAV[8]

1.3 Bio-Mimicry of MAVs

Bio-mimicry is a term for the attempt to imitate nature’s living organism in what that particular organism performed best at. Generally, airplanes utilize the fluid flow surrounding its airfoil-shape wings and can only manipulate the fluid flow to a certain limit under high speed state (high Reynolds number regime). Unlike those steel birds, nature presents fliers that can fully manipulate the flow around its wings and can even keep itself afloat in midair, in a calm, almost stagnant flow environment (low Reynolds number regime), by flapping its wings accordingly.

There are two types of natural fliers; birds (also known as ornithopters as referred by biologist) and insects, in which the latter has a higher degree of complexity when it comes to flight kinematics, in order to fly and hover in an extremely low Reynolds number flow condition. The type of animal selected for mimicry purposes is directly related to its importance towards a specific aerodynamic characteristic that the designed MAV wants to achieve, which is notably the aerodynamic characteristic the selected animal excels best.

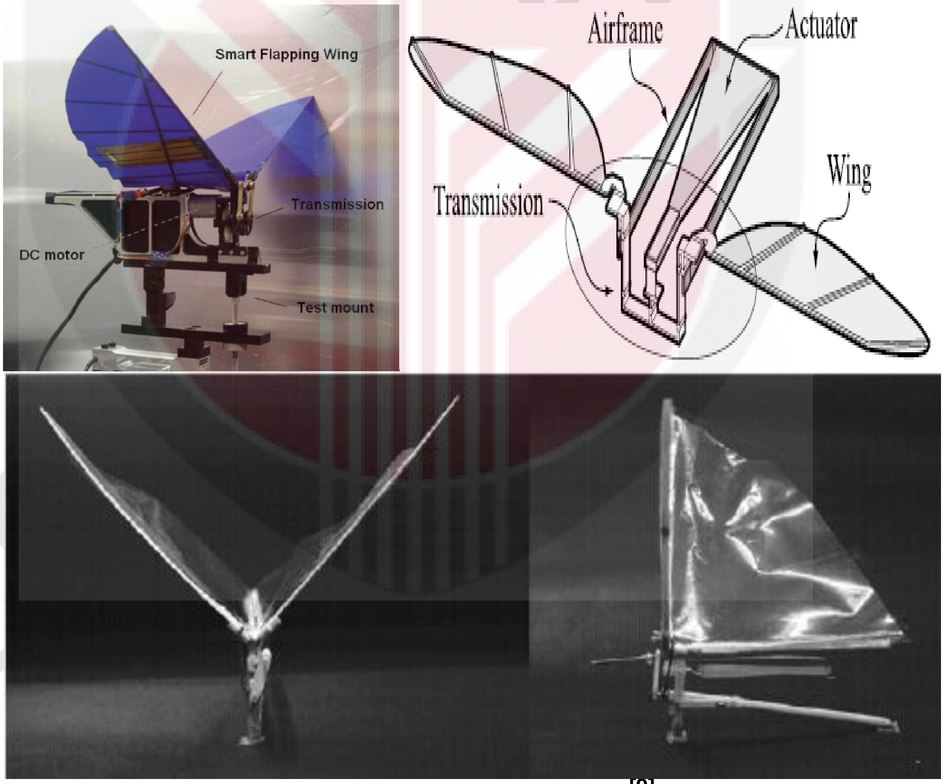

Figure 1.2: Various flapping wing MAV models[9]

This thesis focuses on the Kingfisher bird family, specifically the Oriental Dwarf species, *Ceyx erithacus*, which can be found in Peninsular Malaysia. The fascination towards the Oriental Dwarf Kingfisher is based on its ability to produce constructive aerodynamic characteristics to enable it to manoeuver freely in the air and under water on a regular basis. Furthermore, its specifications of being smaller than 15cm in span and being one of the only bird species that stands at the fine line between ornithopter-like flight and insect-like flight (e.g. hummingbird flaps its wings in an insect-like manner) while maintaining ornithopter-like flapping wing motion under low Reynolds number regime (insect's Reynolds number regime).

Figure 1.3: Kingfisher bird reference for this research; (A) Oriental Dwarf Kingfisher[10] and (B) a Kingfisher diving into water to feed[11]

1.4 Numerical Importance of MAV Designs

Numerical approaches in research development are also equally important as experimental approaches, but dealing with modelling and simulation necessary for numerical analyses have presented its own challenges. Bansmer et al.[12] and Gomes et al.[13] both conducted experimental and numerical studies of airfoils, which the former focuses more on the structural aspects, such as the rigidity and the flexibility of the seagull hand-foil-inspired airfoil, and the latter focuses on laminar fluid-structure-interaction aspects.

Aiding the numerical research, Mazaheri and Ebrahimi conducted experimental investigations, using modern computational power and experimental setups, on the aerodynamic performance of a flapping wing vehicle in forward flight[14] and hovering flight under the effects of chord-wise flexibility[15]. They also performed a series of wind tunnel tests to investigate the cruise performance of a typical flapping wing MAV and published it shortly after[16]. Li and Nahon conducted a numerical investigation as well and recommend a more systematic approach of thrust force estimation for nonlinear dynamics of a flapping wing MAV[17].

Numerical approaches may have more advantages but it is inevitable that high technological aid comes with a high price to pay, as well as time consumption. As concluded by Liu and Aono[18], it takes up to 10 hours to simulate only 4 flapping cycles of a hawkmoth model. Zhang et al.[19] even proposed a justification where a MAV can be treated as a rigid body with only 6 degrees of freedom in order to simplify the model and reduce time and cost of the simulation.

1.5 Problem Statement

Micro-Aerial-Vehicles are dominant used for reconnaissance and search-and-rescue missions, though military uses of MAVs are gaining more attention by the day. These purposes are not restricted only during fine weathers since reconnaissance and search-and-rescue missions could be in dire need outside the benefits of a good weather forecast. The second most common weather that could occur would be rainy. Unfortunately, no research has been made to cater the instability that comes by launching a flapping wing MAV during rainy weather.

As size is a limiting factor, the flight capabilities of said MAV is subjected to how well the MAV could perform under low Reynolds number. The complexity of flapping flight under low Reynolds number regime is immense, given the unsteady transition fluid flow characteristics shown within the flight regime. Flapping flight under such circumstance in itself presents a fair complexity in maintaining flight performance since transition fluid flow can mean that both steady and unsteady fluid flow characteristics are present during the course of the flight. Thus, by adding the uncertainty of weather elements during flight, the complexity of numerically simulating a flapping wing MAV flying through rain environment would be of a higher level of difficulty considering the stacked of unknowns, and producing a fully functional prototype would be of even higher levels.

Most MAV researches up-to-date have only focused on singular flight environment, which predominantly would be air since venturing into the field of multi-environment flapping flight presents a lot of difficulties. Limited researches have been found using an element called “gust” in the attempt to introduce a new flight environment by manipulating air inlet to simulate real-life “pulse” or “oscillating” wind patterns. Researches involving gust are brilliant as birds deal with such difficult adaptations on a daily basis but leaving out other possible elements such as rain would be a terrible lost in the advance of MAV technology.

Kingfishers and some other bird species have known to deal with watery environments on the same basis due to its feeding habits and preferred nesting habitats along rivers and lakes. Weather and terrain patterns are also factors which defines the very nature of these birds as frequent guest to unexpected, high dampness, and watery environments. These birds could fly through rain and could even paddle themselves underwater for a brief moment, as if they were amphibians, despite the necessity. Till today, limited or no research has been done to identify and analyze the flow patterns on the wings of these types of birds and the benefits of implementing said wings in the attempt to provide better chances in producing an all-weather flapping wing MAV.

1.6 Contribution of the Present Research

By considering another important element in bird flight, water can be seen as a daily encounter for survival for the Kingfishers. This research will contribute in the field of wing aerodynamics by providing and analyzing flow patterns produced around a wing model based on a Kingfisher’s wing during Single- (in ambient air environment only) and Multi-phase flight. The Multi-phase flight will consider a simulated rain environment as the second phase environment along the flight path of the wing model.

Therefore, this research can provide significant data on Multi-phase flight which can be utilized to produce an all-weather MAV. This is an important aspect which we need to deepen our understanding and widen our knowledge in order to assist future MAV development in espionage, rescue, scouting, surveying, and other military focused missions in less forgiving terrain and weather.

1.7 Objective of the Research

The objective of this research is to provide essential information on inter-domain flight of a Kingfisher. Rigid and flexible wing has been adopted for research and progresses in that order as to simulate a more realistic numerical analysis. Ultimately, the objectives of this research can be listed as follows:

1) To provide Lift, Drag, and Thrust force analyses on Rigid Kingfisher-inspired Flapping Wing (Single-phase).
2) To compare aerodynamic performance of Flexible Flapping Wing with its Rigid counterpart at optimal flight condition (Single-phase).
3) To analyse aerodynamic changes between Flexible and Rigid Flapping Wings at impact point with Rain environment (Multi-phase).
4) To analyse aerodynamic performances of Flexible and Rigid Flapping Wings after impact with Rain environment (Multi-phase).
5) To validate the simulation results of the Kingfisher-inspired flapping wing's aerodynamic performance with existing researches on different bird-inspired flapping wing model of close similarity in dimensions.

1.8 Scope of the Research

The scope of this research are as follows; first, an introduction on bio-mimicry system is presented and then mimicking flying animals is discussed, followed with wing design of rigid and flexible nature, contribution of both towards generated lift, drag, and thrust forces in air. Ultimately, the flexible wing will be tested under inter-domain flight from air to water environment, which is to be assumed rain and generated lift, drag, and thrust force changes on impact will be observed and analyzed.

1.9 Thesis Outline

This thesis is organized in seven chapters. Chapter 1 deals with introduction to Micro Air Vehicles (MAVs). The rationale for carrying out this research, its objectives and scope are presented in the introductory chapter. Chapter 2 provides the background of this study by reviewing relevant literatures in this field. The effectiveness of flapping wing used for MAVs is discussed in this section. Moreover, a review of previous work dealing with aerodynamic enhancement and other parametric studies carried out to improve the flight performance of MAVs are discussed. Chapter 3 explores the methodology of developing experimental and numerical models, including the fluid dynamic and dynamic mesh theories involved in the developing process and the conducted validations. Results, analyses, and discussions on aerodynamic performance of the main flapping wing model simulations and parametric studies (including multi-phase flight conditions) are presented and compared in Chapter 4. As a closing statement, Chapter 5 discusses on the conclusion and recommendation for future research deduced from this research.

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BIODATA OF STUDENT

Mohd Firdaus Bin Abas was born on 24 December 1987 into a family of 4 siblings. Born in Kuala Lumpur, he received his primary and secondary school educations in Johor Bahru. Then, he pursued his foundation years at Melaka Matriculation College (MMC) for 2 years before he was accepted into Universiti Tun Hussein Onn Malaysia (UTHM) in pursuing his Bachelor Degree in Mechanical Engineering and Manufacturing.

Upon graduating, he immediately pursues his Master Degree in Mechanical Engineering at the same university with additional merits on Computational Fluid Dynamic (CFD) discipline. His dedication towards CFD studies eventually leads him to pursue his Doctoral Degree (PhD) in Engineering at Universiti Putra Malaysia (UPM). There, he met his honorable supervisor, Associate Professor Ir. Dr. Hj. Kamarul Arifin Bin Ahmad, who happens to be one of his late father’s trusted acquaintances.

He married his beautiful wife, Intan Idzadja Hidayah Bt Ab.Hafidz, in his second year of PhD and has been happily together ever since.

LIST OF PUBLICATIONS

Journal

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