UNIVERSITI PUTRA MALAYSIA

THEORETICAL FOUNDATION AND NUMERICAL ANALYSIS ON COANDĂ EFFECT FOR MICRO-AIR VEHICLE

RIYADH IBRAHEEM AHMED

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THEORETICAL FOUNDATION AND NUMERICAL ANALYSIS ON COANDĂ EFFECT FOR MICRO-AIR VEHICLE

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By

RIYADH IBRAHEEM AHMED

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

September 2016

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DEDICATION

To My Dear Country Iraq and My Marvelous Family

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

THEORETICAL FOUNDATION AND NUMERICAL ANALYSIS ON COANDĂ EFFECT FOR MICRO-AIR VEHICLE

By

RIYADH IBRAHEEM AHMED

September 2016

Chairman : Associate Professor Ir. Abd. Rahim Abu Talib, PhD
Faculty : Engineering

Motivated by the need to relate various design parameters of Coandă Micro Air Vehicle (MAV) for its design operation and development, an integrated approach has been undertaken statement that is to develop a workable theoretical analysis that can be utilised as a baseline to design a MAV that can operate effectively in various environmental conditions. The first approach is the analytical, which capitalizes on the basic fundamental principles. The second is the utilization of Computational Fluid Dynamics (CFD), which is based on Navier-Stokes equation for viscous fluid to simulate configurations considered in the analysis, to assess the analytical results, to serve as guideline in developing the analytical model and to provide visualization, and significant insight in identifying the pertinent, problem, to validate the results and to assess the plausibility of the analysis.

In the theoretical analysis, care has been taken in identifying the geometrical parameters of the MAV physical properties of the environment and medium, and the motion of the vehicle at the atmosphere. For the motion of the MAV, basic flight dynamics treatment of the vehicle as a free body mass particle has been followed to derive the basic governing equations. The governing equations for Coandă MAV in hover and translatory motion have been developed and given the understanding of the relationships between relevant Coandă MAV parameters for design and operation purposes.

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The mathematical model and derived performance measures have shown the capability of the theoretical model and analysis in describing the physical phenomena of the flow fields of the semi-spherical Coandă MAV as well as of the cylindrical Coandă MAV. These models provide fundamental tools for the analysis and estimation of Coandă MAV lift generation. In summary, the two approaches have been able to offer the working relationships among various design parameters for the design and operation of Coandă MAV, which are novel and have not been formulated elsewhere as in this work. The results of the analysis are believed to be useful for conceptual or preliminary design sizing of Coandă MAV's, and can be used in the estimation of their lift and other performance measures.

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TEORI ASAS DAN ANALISIS BERANGKA TERHADAP KESAN COANDĂ KE ATAS KENDERAAN MIKRO UDARA

Oleh

RIYADH IBRAHEEM AHMED

September 2016

Pengerusi : Prof. Madya Ir. Abd. Rahim Abu Talib, PhD
Fakulti : Kejuruteraan

Didorong oleh keperluan untuk menghubungkait beberapa parameter reka bentuk bagi Coandă kenderaan mikro udara (MAV) untuk operasi dan pembangunan reka bentuknya, satu pendekatan bersepadu telah diambil untuk membangunkan satu analisis teori yang boleh dilaksanakan bagi digunakan sebagai asas untuk mereka bentuk satu MAV yang boleh beroperasi dalam pelbagai kondisi persekitaran. Pendekatan pertama adalah analitikal yang bermodalkan prinsip dasar asas. Pendekatan kedua adalah penggunaan Komputasi Dinamik Bendalir (CFD) yang berasaskan persamaan Navier-Stokes bagi bendalir likat untuk mensimulasikan konfigurasi yang diambil kira dalam analisis, mentaksir keputusan analitikal, menjadi garis panduan dalam membangunkan model analitikal dan menyediakan pembayangan serta wawasan bererti dalam mengenalpasti masalah yang relevan di dalam pernyataan masalah bagi kerja ini agar dapat mengesah keputusan dan mentaksir kemungkinan analisis.

Dalam analisis teoritikal, perhatian telah diberikan dalam mengenal pasti parameter geometri MAV, sifat fizikal persekitaran dan medium, dan gerakan kenderaan dalam atmosfera. Bagi gerakan MAV, olahan asas dinamik penerbangan bagi kenderaan ini sebagai zarah jisim badan bebas telah diikuti untuk menerbitkan persamaan menakluk asas. Persamaan menakluk bagi Coandă MAV dalam gerakan hover dan luncur telah dibangunkan dan memberikan kefahaman mengenai perkaitan di antara parameter Coandă MAV yang relevan bagi tujuan reka bentuk dan operasi.

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Model matematik dan pengukur prestasi yang dibina telah menunjukkan kemampuan model dan analisis teoritikal dalam menerangkan fenomena fizikal medan aliran bagi Coandă MAV separuh-sfera serta Coandă MAV silinder. Model ini menyediakan alat asas untuk analisis dan penganggaran penjanaan daya angkat bagi Coandă MAV. Sebagai kesimpulannya, dua pendekatan yang diambil telah mampu menyediakan perkaitan di antara pelbagai parameter reka bentuk yang boleh digunakan dalam mereka bentuk dan operasi Coandă MAV, yang mana ianya novel dan belum dirumuskan di tempat lain seperti dalam kerja ini. Keputusan analisis dipercayai berguna untuk pensaizan reka bentuk konsep dan permulaan Coandă MAV serta boleh digunakan untuk penganggaran daya angkatnya dan pengukuran prestasinya yang lain.

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بسم الله الرحمن الرحيم

"مَن كَانَ يُرِيدُ الْعِزَّةَ فَلِلَّهِ الْعِزَّةُ جَمِيعًا ۚ إِلَيْهِ يَصْعَدُ الْكَلِمُ الطَّيِّبُ وَالْعَمَلُ الصَّالِحُ يَرْفَعُهُ ۚ وَالَّذِينَ يَمْكُرُونَ السَّيِّئَاتِ لَهُمْ عَذَابٌ شَدِيدٌ ۖ وَمَكْرُ أُولَٰئِكَ هُوَ يَبُورُ" (10) (فاطر)

"In the name of Allah the most beneficent and merciful"
Blessing and peace be upon our Prophet Muhammad (S.A.W)

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Thanks go to my employer the Ministry of Science and Technology-Iraq who given me the opportunity to gain higher education standard.

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I certify that a Thesis Examination Committee has met on 29 September 2016 to conduct the final examination of Riyadh Ibraheem Ahmed on his thesis entitled "Theoretical Foundation and Numerical Analysis on Coanda Effect for Micro-Air Vehicle" 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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Name of Member of Supervisory Committee: Senior Lecturer Dr. Fairuz Izzuddin Romli

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LIST OF ABBREVIATIONS

2-D	Two dimensional
3-D	Three dimensional
AUV	Autonomous Underwater Vehicle
BEMT	Blade Element Momentum Theory
CC	Circulation Control
CCR	Circulation Control Rotor/Rudder
CCW	Circulation Control Wing
CFD	Computational Fluid Dynamics
CG	Centre of Gravity
C.P	Centre of Pressure
Code	Coded Implementation
DASH	Drone Anti-Submarine Helicopter
CTOL	Conventional take-off and landing
GTRI	Georgia Tech Research Institute
HAWT	Horizontal Axis Wind Turbine DCl
LE	Leading Edge
LES	Large Eddy Simulation
MAV	Micro Air Vehicle
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NREL	National renewable Energy Laboratory
NSRDC	Naval Ship Research and Development Center
NSWC	Naval Surface Warfare Center
NTSB	National Transport Safety Board
RANS	Reynolds-Averaged Navier-Stokes
RC	Radio Controlled
RDTE	Research, Design, Test and Evaluation
RHS	Right Hand Side
RPM	Revolutions per Minute
RWUAV	Rotary-wing Unmanned Aerial Vehicle
SST	Shear Stress Transport
STOL	Short Take-off and Landing
TE	Trailing edge
UAV	Unmanned Aerial Vehicle
UPM	Universiti Putra Malaysia
VAWT	Vertical Axis Wind Turbine
VTOL	Vertical Take-off and Landing

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Greek Characters

A	Rotor area, scaling factor (m^2)
Acs	Cross-sectional area facing the flow (m^2)
A_{jet}	Jet opening area (m^2)
A_{MAV_base}	MAV base area (m^2)
Ar	Cross-sectional area facing the flow at a distance r from blower central axis (m^2)
$Area_{lower-surface}$	MAV lower surface area (m^2)
A_{ref}	Reference surface area of air vehicle (m^2)
c	Airfoil Chord (m)
C	Wing chord length (m)
C_D	Drag Coefficient
C_L	Lift Coefficient
C_{Lmax}	Maximum lift coefficient
Cm	Moment Coefficient
C_p	Pressure coefficient
C_T	Thrust coefficient
$C\mu$	Jet moment coefficient (Coandă)
C_v	The specific heat at constant volume
d	Fan diameter (m)
D	Drag Force (N)
D	Rotor diameter (m)
dS	Propeller disk area (m^2)
E	Wall roughness parameter for smooth walls E= 9.8
F	Force (vector)
Fa	Horizontal or axial force component (N)
Fc	Centrifugal force acting on Coandă body(N)
$F_{Coandă\ jet-blanket}$	Force from the Coandă Jet blanket (N)
$F_{Induced\ pressure\ difference}$	Force from pressure difference between upper and lower parts of the MAV body (N)
$F_{lower-surface}$	Force from the pressure difference on the lower surface of the MAV body (N)
F_N	Normal or vertical force component (N)
Fp	Pressure force acting on Coandă body (N)
$F_{pressure\ difference\ lower\ to\ upper}$	Force from the pressure difference between the upper part and the lower part of the MAV body (N)
F_{total}	Total lift for the cylindrically shaped Coandă MAV (N)

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$F_{upper\text{-}surface}$	Force from the pressure on the upper surface of the MAV body (N)
F_{upward}	Lift from the momentum flux through the control volume CV in y-vertical direction (N)
$f_{downward}$	Pressure force acting on upper surface of the cylindrical shape MAV (N)
f_{upward}	Pressure force acting on lower surface of the cylindrical shape MAV (N)
g	Gravitational acceleration (m/s^2)
grad U,V,W	$\partial(U,V,W)/\partial x + \partial(U,V,W)/\partial y + \partial(U,V,W)/\partial z$
h	Jet slot thickness on Coandă surface (m)
h	Height above ground level
hi	Inlet jet slot thickness (m)
h_0	Outlet Jet thickness (m)
k	Turbulence parameter the kinetic energy term
l	Length of the cylindrical shape MAV (m)
L	Lift (N)
L/D	Lift to drag ratio
L/W	Lift to weight ratio
Lift Coandă jet Blanket + Induced pressure difference	Total lift force due to Coandă Blanket (N)
Lift Cylindrical-Coandă-jet blanket +Induced pressure difference	The resultant forces that contribute the lift of the cylindrical Coandă MAV (N)
Lift Spherical-Coandă jet blanket +Induced pressure difference	Total lift due to Coandă jet blanket momentum and induced pressure difference for spherical Coandă MAV (N)
M	Structural mass (kg)
M	Mach number
$\dot{m}$	Mass flow rate (kg/s)
P	Power (Watt)
p	pressure, load (Pa)
P_a	Atmospheric pressure (Pa)
P_{atm}	Atmospheric pressure (Pa)
pc	Centrifugal load (Pa)
P_{lower}	Pressure at the lower surface of MAV (Pa)
$PM1,2,3$	Performance Measures 1, 2 and 3
$PM_{\substack{Coandă-MAV \\ LevelFlight}}$	$= \dfrac{Power\ required\ to\ overcome\ Drag}{Power\ Input\ by\ Coandă-jet-action}$

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$PM_{\substack{Coand\breve{a}-MAV \\ Climbing}}$	$= \dfrac{Power\ required\ to\ Climb}{Power\ Input\ by\ Coand\breve{a}-jet-action}$
Power $_{output}$	Power output from the system (watt)
Power $_{input}$	Power input to the system (watt)
P_R	Pressure along the Coandă curved surface (Pa)
P_s	Body surface pressure (Pa)
P_{upper}	Pressure at the upper surface of Coandă MAV (Pa)
Np	Load normal to rotor plane
Q	Rate of heat transfer
q	The free-stream dynamic pressure (Pa)
R	Radius of Coandă curved surface (m)
R'	Radius of Coandă curved surface at any point $R'=R\ sin\theta$ (m)
R_0	MAV outer radius (m)
Re	Reynolds number
R_i	Jet slot radius (m)
S	Surface area (m^2)
s	Surface path (m)
t	Jet thickness at outer surface edge (m)
t	Time
T	Thrust
T	Horizontal or vertical thrust generated (N)
T_{atm}	Atmospheric temperature (0C)
t_{max}	Maximum aerofoil thickness (m)
Tp	Thrust generated by a ducted propeller (N)
t_{TE}	Wall-jet flow depth at trailing edge (m)
T_{req}	Thrust required for VTOL (N)
$T_{Coand\breve{a}-MAV}$	The total generated force vector (N)
u	Local flow velocity (m/s)
U	Boundary layer edge velocity (m/s)
U	The instantaneous streamwise velocity (m/s)
$\bar{U}$	The mean component (m/s)
u	The fluctuating component of velocity (m/s)
$\ddot{u}$	Structural acceleration (m/s^2)
u_1	Velocity in wake (m/s)
U_{eff}	Effective flow velocity (m/s)
$u_{m/2}$	Mean jet velocity at $y_{1/2}$ (m/s)
U_{max}	Maximum flow velocity at outlet (m/s)
Ur	Flow velocity at a distance r (m/s)
U_{ref}	Flow velocity at quarter chord (m/s)

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Ux	Translational velocity (m/s)
u_τ	The friction velocity (shear velocity)
$u+$	The wall function of turbulent flow
v	Local flow velocity (m/s)
V	Velocity (vector)
vy	Component of velocity vector
$V2$	Velocity in rotor plane for a shrouded rotor
V_∞	Freestream Velocity(ambient) (m/s)
$V_{Coandă\ jet}$	Coandă jet velocity (m/s)
$V_{j\text{-}in}$	Jet inlet velocity (m/s)
$V_{j\text{-}out}$	Jet outlet velocity (m/s)
$V_{j\text{-}R}$	Wall-jet velocity (m/s)
V_{ref}	Approach speed (m/s)
V_θ	Tangential velocity component
$\dot{V}$	The air vehicle acceleration axial component (m/s^2)
$\vec{v}$	Velocity vector
W	Weight (N)
w	Induced velocity
Wy	Tangential component of induced velocity
Wz	Normal component of induced velocity
Ẃ	Weight-Fuel Consumption
ym	Radial distance from surface to the point where u=um (m)
y+	Dimensionless wall distance of the boundary layer
$\ddot{y}$	The vertical acceleration component (m/s^2)
α	Angle of attack (rad)
δ	Boundary layer thickness
ε	Dissipation per unit mass
ε	The angle made by the axis of rotation of the rotor with the freestream velocity vector (rad)
η_L	Lifting efficiency
θ_{sep}	Separation Angle of Coandă jet (rad)
θ_0	Jet flow separation angle (rad)
θ_i	Jet flow injection turning angles (rad)
μ	Dynamic viscosity (N.s/m^2)
μ_T	Turbulent/eddy viscosity (kg/m.s)
ν	Kinematic viscosity, wind shear exponent (m^2/s)
ρ	Air density at sea level (=1.225 kg / m^3)
ρ_j	Jet flow density (kg / m^3)
$\rho\infty$	Density of free stream (kg / m^3)

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τ	Shear stress, time constant (pa)
$\bar{\bar{\tau}}$	The stress tensor
ω	Angular velocity of rotor
ω	Dissipation per unit turbulence kinetic energy
$\partial C_L / \partial \alpha$	Lift curve slope
γ	Flight path angle
$\alpha, \beta, \beta^*, \sigma, \sigma^*$	Closure coefficients

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CHAPTER 1

INTRODUCTION

1.1 Overview

"At the present time no known man made UAV stands any chance of matching the performance of Coandă Micro vehicles"
(Adapted from Collins, 2002)

Coandă Micro Air vehicles (MAVs) could be predicted to be the next, emerging generation of aerospace systems, with many potential applications in both civilian and military missions. In this regards, Coandă MAV, as an active controlled and vertical take-off and landing aircraft (VTOL), can be truly described as a new airspace platform, since the record in the literature and researches have not so far revealed a mature concept and a new operational air vehicle or presently under development. Consequently, one may begin exploring the Coandă MAV concept with the applications to Coandă MAV principles. As the field of Coandă MAV, which is a VTOL air-vehicle evolved, much attention was paid to Coandă MAV lift and propulsion system considerations and development of the governing aerodynamic theory. Other subjects included design studies of configurations and control issues during hover and transition, as depicted in Figure 1.1, which to the best of the author's knowledge have not received sufficient attention thus far.

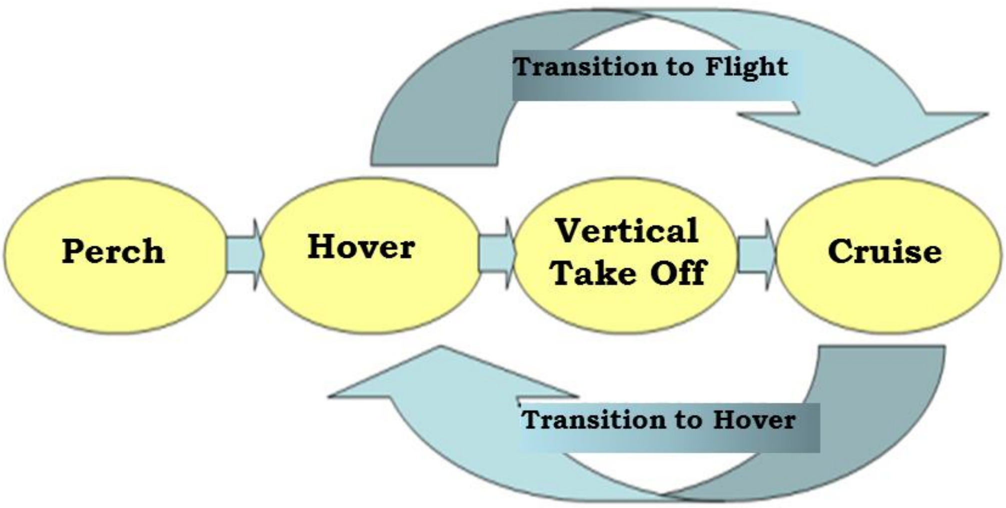

Figure 1.1: Flight Manoeuvring Structure of Coandă MAV (Modified from Frank et al., 2007)

As radical new air vehicles that combine state of the art technologies in a new and synergistic manner is one which uses the Coandă effect to develop lift and propulsion.

For designing a Coandă MAV, which could meet the desired mission and design requirements, it is mandatory to establish the basic working relationships between various relevant variables and parameters governing the aerodynamics forces.

Insufficient knowledge, predictive capabilities, and experimental data exist regarding the fundamental unsteady aerodynamics of low Reynolds number flyers, and the associated fluid-structure-control interactions and flight mechanics on Coandă MAV.

Such brief but comprehensive view on Coandă MAV development thus far, which will be further elaborated in the literature review, motivated the author to pursue the issue as formulated in the problem statement, and develop a working principles, as a baseline, for design and operation. To assist the analysis, design, and developments of Coandă MAV's, several tools can be resorted to. The first is the analytical tool, which capitalizes on the basic fundamental principles. The second is the utilization of Computational Fluid Dynamics (CFD), which has the advantage of providing visualization for significant insight and identification to the problem at hand, which then can be utilized in enhancing the analysis and identifying specific details.

Other tools such as experimental, which are not covered here although some attempt was executed to have a demonstration model for its practicality, can benefit from the insight gained by analysis, CFD computational and visualization studies.

By referring to Figure 1.2, representing an impression of the possible Coandă MAV qualitative performance in comparison to other flight vehicles, it would be of interest to investigate the principle of Coandă MAV Lift generation as well as its performance in hover and forward flight.

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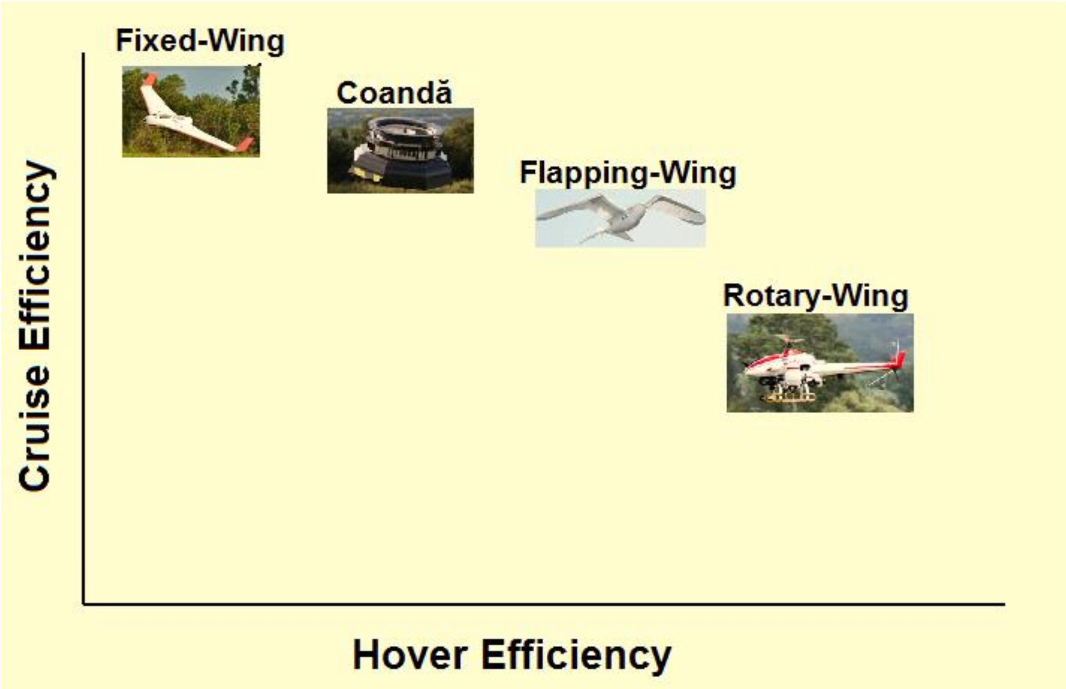

Figure 1.2: Coandă MAV qualitative performance in comparison to other flight vehicles. (Modified from Schroijen and van Tooren, 2009)

1.2 Problem Statement

Micro Air Vehicles (MAVs) can be used in variety of missions, for civilian and military operations, that required to perform a steady positioning for surveillance and monitoring and to accomplish a good manoeuvrability within an unstable atmosphere. Then, the problem faced is to develop a workable theoretical analysis that can be utilised to design a Micro Air Vehicle (MAV) that can operate effectively in various environmental conditions.

It should be kept in mind that various factors, which incorporate vehicle geometrical and physical properties, environmental conditions and physical properties, and the relative motion between the vehicle with respect to the environment, which should be identified and elaborated. One example is the role and influence of Circulation Control using Coandă effect.

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1.3 Thesis Objectives

Based on the problem statement, the research objectives can be elaborated as follows:

i) To establish relevant governing equations from first principles on the Coandă effect for the Coandă MAV as the basis of their physical and mathematical modelling and their further analysis and performance.

ii) To analyse numerically the Coandă effect on Coandă MAV by carrying out computational fluid dynamic (CFD) techniques and numerical simulation utilizing appropriate computational routine.

iii) To assess the applicability of the Coandă MAV theoretical analysis based on first principle analysis and CFD numerical simulation in synthesizing the working principle of basic Coandă MAV configuration appropriately.

In this regards it is noted that theoretical foundation provides essential vision, and CFD simulation incorporates additional information not considered in the theoretical analysis such as the effect of viscosity, details influence of the boundary conditions and the flow field

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1.4 Hypothesis and Research Questions

1.4.1 Hypothesis

To carry out research work associated with the problem statement and objective, some assumption and research hypothesis will be formulated as a guideline. Basic assumptions that will be adapted in this work are that the Coandă MAV can be modelled as a simple configuration that will represent the main elements for producing Coandă jet effects. The analysis will assume the fluid as incompressible and in the motion of Coandă MAV; the latter can be treated as a point Mass rigid body. The CFD simulation study that will be resorted to is chosen to be based on viscous flow, i.e. the Navier Stokes equation. The following hypothesis can be formulated

- In the physical and mathematical modelling, the dynamics of Coandă MAV can be formulated using conservation principles in fluid dynamics and rigid body motion in flight dynamics.
- The governing equations derived using the above approach can be utilised for sizing and developing parametric studies in the conceptual design, as well as modifying the governing equations for other configurations.

1.4.2 Research Questions

The fundamental research questions elaborate the means and methods formulated in the hypothesis. The hypothesis is an intuitive answer to the problem statement and objective of the research, based on assumptions that have to be taken to isolate the problem in order to obtain workable solution. The fundamental research questions are: How can a mathematical model for a Coandă MAV that utilized for conceptual design prediction and limited optimisation be significantly improved upon, and, to what extent could an improved Coandă MAV design be produced there after?

Then the research question related to the hypothesis can be formulated below, as related to the analytical, CFD simulation and demonstration experiment carried out in the present study.

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Study	No.	Research Problems
Analytical	RQ1	Find the governing equation of the Coandă MAV in hover
	RQ2	Find the governing equation of the Coandă MAV in Translation
CFD simulation study	RQ3	Verify the analytical prediction using CFD simulation
	RQ4	Elaborate the contribution of CFD simulation to the mathematical modelling in analysis

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1.5 Scope and Limitation

1.5.1 Scope

The scope of study is only on a basic Coandă fluid dynamics and flight dynamics without going into other details like additional control surfaces and complex configuration. The research plan and the work methodology, including the milestone of achievements were managed according to the research proposal and thesis objects following the research time schedule. Special attention to be given on the modelling and prototyping concept of Coandă jet, to generates lift of micro air vehicles. The work scope can be summarized to be covering the following Research Elements:

- To review of Coandă effect, and to establish schemes for improvements in terms of lift enhancement on Coandă MAV.
- To carry out theoretical analysis and Computational fluid dynamic CFD simulations of sets of Coandă MAV models. These integrated Coandă MAV models (Semi-spherical and Cylindrical Shapes) based on the analytical study and numerical analyses were developed.
- To devise a propulsion system with Coandă effect controlled configuration to investigate the effect of certain strategies to alleviate Coandă jet impact. The work focuses on the aerodynamic aspects of Coandă circulation control concepts, for two dimensional 2D and three dimensional 3D models, for steady flow at zero degree angle of attack and with the variation of geometrical parameters of the MAV configurations, such as;
  - MAV body sizes (diameter)
  - Jet thickness (slot opening)
  - Jet Momentum (jet speed)
  - Jet Location
- To Carrying out an investigation of the principle of Coandă MAV, lift generation as well as its performance in hover and forward flight. Using modelling and proof concept of prototyping by the means of:
- Formulations and Utilization of First Principles as the analytical tool, which capitalizes on the basic fundamental principles.
- CFD simulation: the utilization of Computational Fluid Dynamics (CFD), using commercial software ANSYS Fluent

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(Swanson Analysis System, Inc.), to provide visualization and significant insight in identifying the relevant problem. Theoretical analysis and CFD visualization studies will be useful in the preliminary study stage, as well as in designing specific experiments in the conceptual and prototype design stages.

All materials, equipment, models, tools and hardware's to support this research study, with a licensed software, ANSYS Fluent available for CFD simulation of the generic Coandă Effect, were made available by the Aerospace Engineering Department, Engineering Faculty, Universiti Putra Malaysia (UPM). The analytical and computational simulation has been carried out for many cases and the results were analysed accordingly.

1.5.2 Limitation

The work is only limited to answer the objective and research questions that can be used as a baseline for Coandă MAV mechanics and design. The parametric study is focussed on two-dimensional steady flow and the theoretical analysis will not consider the effects of viscosity and velocity profile, which is instrumental in gaining insight into the problem. Viscous effects are dealt with in the CFD analysis and simulations.

The idealization on the flow condition and the focus on two-dimensional flow process are aimed to produce flow situation, which will be assisted by CFD analysis.

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1.6 Outline of Thesis

The research thesis was divided into nine main chapters that cover systematically the whole work, and are outlined briefly as follows:

- Chapter One; concludes an overview of the system, motivating the problem statements, along with the principal objectives of the present study. More details related to the thesis hypothesis and research questions as well as the thesis scope and limitation have been briefly explained.
- Chapter Two; provides a scientific literature review and previous work focused on the publications dealing with the issue of designing of Coandă MAV. In this chapter, an effort to classify of mini size UAVs and provide an insight into this rapidly growing field is prepared. Special aspects of aerodynamics performance for typically mini size UAVs are discussed in relation to their motion applications. The foundation of Coandă MAV is described in full details.
- Chapter Three; outlines of the methodology of the research in this thesis which is incorporated of various studies, analytical study, and numerical analysis that are intended to be developed. The numerical analysis is elaborated to show details of the governing equations, the formulation of the Navier-Stockes equations, and the computational set up.
- Chapter Four; this chapter was divided into two main sections. The first, describes the development of the mathematical models for the two baseline Coandă MAVs (semi-spherical and cylindrical models) with elaborated derivations. The second section provides details of the derivations of the fluid dynamic and flight mechanics of the Coandă MAV, in hover, cursing and forward flight.
- Chapter Five; explains the computational fluid dynamic analysis conducted in the present work. The body geometry the grid generation and the mesh independency test are discussed in details. More details are given related to the turbulent models used in the present study.
- Chapter Six; present in details the analysis results, verification validation, discussions, and an overview of the whole study.
- Chapter Seven; presents the conclusions section, looking back at the various topics touched upon this thesis, attempting to objectively evaluate the results obtained. The recommendations for future work in terms of both possible improvements and new research directions are described.

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Other details may be added to include some essential information's as will be presented in the Appendices. Outline of the thesis is depicted in Figure 1.3.

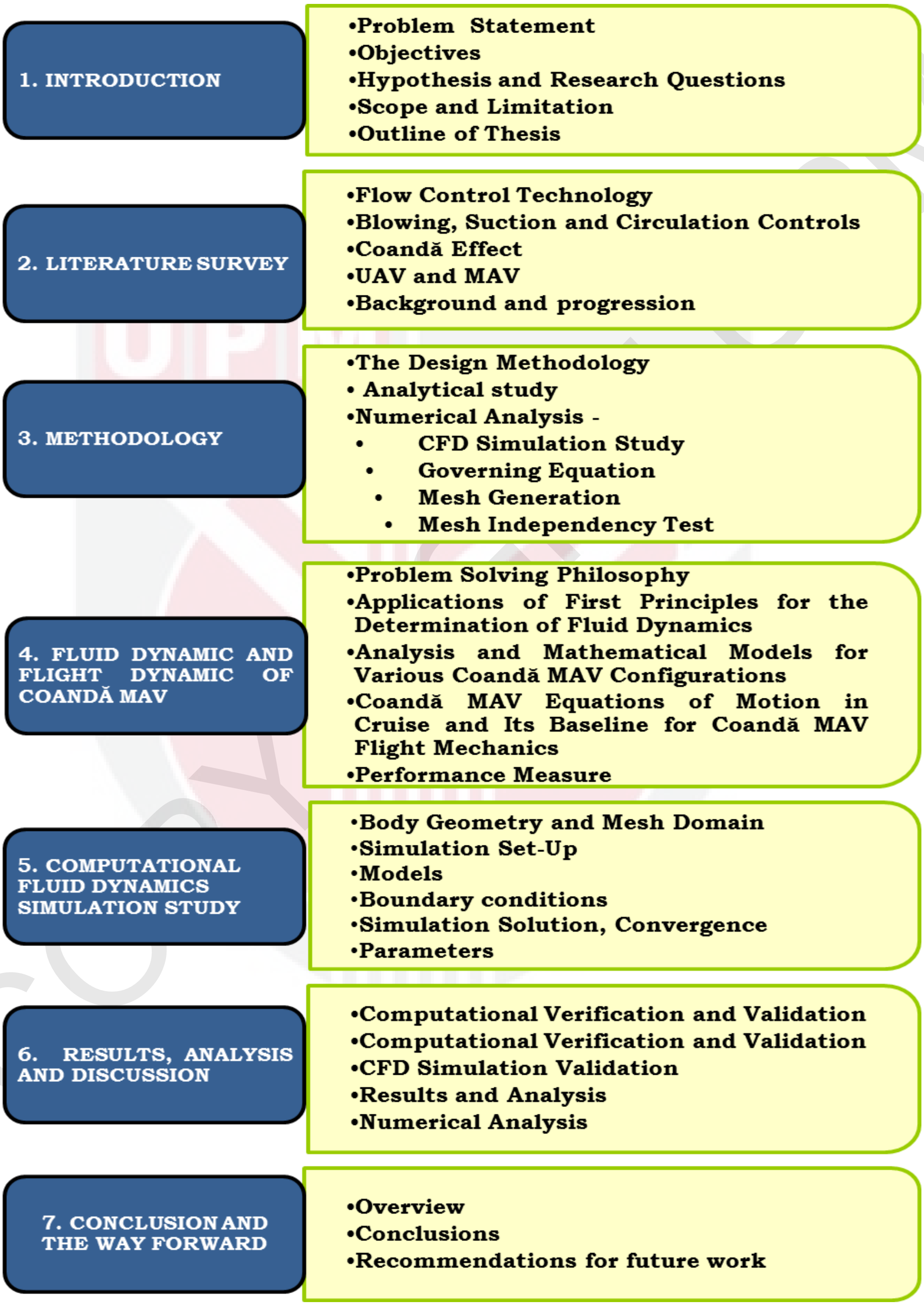

Figure 1.3: Thesis outlines

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