UNIVERSITI PUTRA MALAYSIA

MATHEMATICAL MODELLING OF AERODYNAMIC CHARACTERISTICS FOR FLAPPING WING ORNITHOPTER

ALIF SYAMIM SYAZWAN BIN RAMLI

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By

ALIF SYAMIM SYAZWAN BIN RAMLI

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October 2015

Chair: Prof. Harijono Djojodihardjo, PhD, Ir
Faculty: Engineering

Natural cycle and creation has led to some really efficient flying creatures. It is important to look at the criteria, characteristic and constraints in order to understand how the mechanisms, principles and natural design are aerodynamically achieved. The objective of this study is to establish the salient features and functional implication from various components characterized from the dynamics, kinematics, and aerodynamics of the flying biosystems, and to synthesize a simple yet comprehensive workable mathematical aerodynamic modelling of flapping wing ornithopter. Considerations are given to the motion of a three-dimensional thin rigid wing in flapping and pitching motion with phase lag. Fundamental unsteady aerodynamic analytical approach using modified strip theory incorporating leading-edge suction and viscous effect is utilized for modelling development. The two-dimensional computational fluid dynamic simulation procedure is done on heaving thin rigid wing using ANSYS-CFX software for validation purpose. For the analytical computation, the first part of the study is focused on a bi-wing ornithopter. Parametric study is carried out to reveal the flapping bi-wing ornithopter aerodynamic characteristics and for comparative analysis with various selected simple models in the literature. Further analysis is carried out by differentiating the pitching and flapping motion and studying its respective contribution to the flight forces. Similar procedure is then applied to flapping quad-wing ornithopter model. The present flapping wing aerodynamic model results computed have been validated satisfactorily with other relevant comparable studies. The analysis of component-wise contribution based on the flapping and pitching motion shows that: (a) The lift is influenced mostly by the incidence angle (b) The thrust is influenced mostly by flapping motion (c) Phase-lag could be utilized to obtain optimum lift and thrust for each wing configurations. For the quad-wing ornithopter at the present stage, the simplified computational model adopted has verified the gain in force obtained as compared to bi-wing flapping ornithopter. All these results which have been satisfactorily validated lend support to the generic modelling development

adopted for the synthesis of flight model. It is also capable to reveal basic characteristics of flapping wing ornithopter that is useful for optimization of geometry, kinematics and aerodynamics design of flapping wing mechanization.

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

MODEL MATEMATIK SIFAT-SIFAT AERODINAMIK ORNITOPTER BERKIBAS

Oleh

ALIF SYAMIM SYAZWAN BIN RAMLI

Oktober 2015

Pengerusi: Prof. Harijono Djojodihardjo, PhD, Ir
Fakulti : Kejuruteraan

Kitaran semulajadi dan penciptaan membawa pada satu ciptaan terbang yang efektif. Adalah penting untuk melihat pada kriteria, sifat dan halangan dalam memahami bagaimana mekanisma, prinsip dan rekabentuk semulajadi dicapai secara aerodinamiknya. Objektif kajian ini adalah untuk memastikan ciri-ciri serta fungsi yang penting melalui kepelbagaian komponen dari aspek dinamik, kinematik, dan aerodinamik biosistem berkibas, dan memsintesis model matematik aerodinamik ornitopter berkibas yang berfungsi dan menyeluruh. Pertimbangan diberi pada gerakan sayap tegar dan nipis tiga dimensi dalam gerakan mengibas bersudut dengan fasa tertentu. Pendekatan asas aerodinamik tak mantap menggunakan teori belahan menggabungkan kesan likat dan sedutan pada bahagian hujung hadapan aerofoil digunakan sebagai model. Prosedur simulasi dinamik bendalir dua dimensi dijalankan pada sayap tegar dan nipis yang berkibas, menggunakan perisian ANSYS-CFX untuk tujuan pengesahan. Untuk pengiraan analisis, bahagian pertama difokuskan kepada pesawat berkibas bersayap dua. Kajian parametrik dijalankan untuk mendedahkan sifat aerodinamik pesawat berkibas bersayap dua dan juga untuk tujuan analisis perbandingan dengan pelbagai model ringkas yang terpilih dalam kajian-kajian sedia ada. Analisis seterusnya dijalankan dengan mengasingkan gerakan mengibas bersudut mengikut komponen dan mengkaji kesan masing-masing secara tunggal pada daya penerbangan. Prosedur yang sama kemudiannya digunakan pada model pesawat berkibas bersayap empat. Hasil model telah disahkan sewajarnya dengan kajian-kajian lain yang relevan. Analisis sumbangan komponen melalui pergerakan mengibas bersudut menunjukkan: (a) daya angkatan dipengaruhi oleh pergerakan mengibas (b) daya tujahan dipengaruhi oleh sudut insiden (c) perbezaan fasa boleh digunakan untuk mendapatkan daya angkatan dan tujahan yang optimum bagi setiap konfigurasi sayap. Untuk ornitopter bersayap empat, ketika ini, model ringkas tersebut menunjukkan peningkatan daya terhasil berbanding yang bersayap dua. Hasil terbukti yang diperoleh mampu memberi sumbangan kepada

perkembangan model umum yang digunakan untuk penghasilan model penerbangan. Ianya juga mampu untuk mendedahkan ciri-ciri asas penerbangan berkibas ornithopter yang berguna bagi tujuan pengoptimuman rekabentuk geometri, kinematik dan aerodinamik pada mekanisasi sayap berkibas.

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I certify that an Examination Committee has met on 15 October 2015 to conduct the final examination of Alif Syamim Syazwan bin Ramli on his thesis entitled "Mathematical Modelling of Aerodynamic Characteristics for Flapping Wing Ornithopter" in accordance with the Universities and University College 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 Master of Science.

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Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Ermira Junita Abdullah, PhD
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Erwin Sulaeman, PhD
Associate Professor
Kulliyyah of Engineering
International Islamic University Malaysia
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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:

Harijono Djojodihardjo, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Azmin Shakrine Mohd Rafie, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Surjatin Wiriadidjaja, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

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Professor and Dean
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Signature:	
Name of Member of Supervisory Committee:	Assoc. Prof. Dr. Azmin Shakrine Mohd Rafie

Signature:	
Name of Member of Supervisory Committee:	Assc. Prof. Dr.-Ing. Surjatin Wiriadidjaja

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LIST OF ABBREVIATIONS

AR	aspect ratio
B	semi-wingspan
C	chord
C(k)	Theodorsen function
$C(k)_{jones}$	modified Theodorsen function for finite wing
Cd_f	drag coefficient due to skin friction
dD_{camber}	sectional force due to camber
dD_f	sectional friction drag
dF_x	sectional chordwise force
dL	sectional lift
dy	width of sectional strip under consideration
dN	sectional total normal force
dN_c	sectional circulatory normal force
dN_{nc}	sectional apparent mass effect
dT	sectional thrust
dT_s	leading edge suction force
F(k)	Theodorsen function real component
G(k)	Theodorsen function imaginary component
$\dot{h}$	plunging rate
k	reduced frequency
L	total lift
L_{fore}	lift force of fore-wing
t	time

T	total thrust
U	flight velocity
V	relative velocity at quarter chord point
V_x	flow speed tangential to section
V_{rel}	relative velocity
V_i	induced velocity
w_0	downwash velocity at ¾-chord point
Γ	circulation
ρ	air density
β	flapping angle
β_0	maximum flapping angle
θ	pitching angle
θ_0	maximum pitch angle
$\theta_{hindwing}$	effective pitching angle of hind-wing
θ_f	angle of flapping axis with respect to flight velocity (incidence angle)
θ_p	mean pitch angle of chord with respect to flapping axis
ϕ	lag angle between pitching and flapping angle
α	relative angle of attack
α'	flow's relative angle of attack at three-quarter chord point
α_0	zero-lift angle
η_s	efficiency coefficient
ω	flapping frequency

CHAPTER 1

INTRODUCTION

It is very interesting to observe anthropogenic system that has been developed from simplest to most sophisticated one, for example, the simplest are toys, but that actually triggered author's attention which leads to that present work. Also, it is observed that mankind has been able to produce new creations emulated based on nature, like aircraft and glider to serve mankind's missions effectively. Based on these remarks, the present work is devoted to flapping wing ornithopter based on simple principles that is feasible to build.

1.1 Background

The desire of human to physically learn from flying biosystems or animals such as insects and birds by mimicking them, has been initiated since hundreds of years back then and enthused creativity of mankind, from inventors like Leonardo Da Vinci and his flying machine to present modern aircraft technology. Nowadays, a research of flapping flight focuses on autonomous unmanned or ornithopter, which requires synthesis of many generic engineering practices incorporating flapping wing aerodynamics, fluid-structure aeroelastic interaction and dynamics of flapping wings. Small reconnaissance ornithopter like micro air vehicle (MAV) are of great interest for their multipurpose flying capabilities, such as flying and hovering indoor as well as outdoor for reconnaissance, and agility to move in confined spaces at low speeds, as well as for disaster monitoring. For this kind of flight envelope, small ornithopter seems to be an optimal mode of flying. Additionally, flapping wing ornithopter can be considered to be an effective and environmentally friendly flight vehicle that mimics natural flyers through synthesizing various technologies.

A comprehensive foundation of force generation in flapping flight is synthesized, even though it is rather limited, for defined knowledge of unsteady forces production by wings is not well-understood yet. Data are specifically lacking in the very low Reynolds number regime -around 10 to 1000- which fits the small insects' flight. Also, animals' flight is one of the most complicated activities found in nature and covers a large diversity of categories with all unified in one sophisticated system. The biological and physical elements like physiology, morphology, ecology, and wing role must be acknowledged in order to understand how the mechanism of real flying animals schemes (Pennycuick, 1990; Rayner, 1993; Dudley, 1999; Lindhe Norberg, 2002). Insect wings are very flexible morphologically, compared with the flying vertebrate groups which follow more conservative fashion. Thus, better understanding on the evolution and adaptation of a structure through combination of physical laws and appearances and behaviour in animals is very essential in order to make a best judgement in selecting optimal structure and form of the flight apparatus to achieve optimized flight locomotion and minimize cost of flight. An overview for establishing an insight for development of flapping ornithopter has been done based on some selected relevant characteristics from flapping biosystems (shown in Table 1.1), where each reveals their different individual flight features and capabilities.

As demonstrated by flying biological organisms, the motion of pitching and flapping in flight of flapping wing offers potential aerodynamic advantages that are only viable through such kinematic, compared with conventional fixed-wing. Taking advantages of these two benefits, for example, can increase the efficiency of flapping flight; (1) The angle of attack for flapping wing can be set to zero during the upstroke theoretically, so that it can pass simply through the air for better flight performance, and (2) usually, since the flapping wings generate both lift and thrust, the structures induced by drag are lessened. Plus, it has been suggested by Mueller and DeLaurier (2001) that these advantages are even greater with smaller size and lower flight speed.

Biosystem's flapping flights are also characterized by relatively low Reynolds number, flexible wing, highly unsteady flow, laminar separation bubble, non-symmetrical upstroke and downstroke and for insects, the presence and significant role of leading edge vortex, and wake vortices capture and some others that seem relevant (Shyy et al, 1999). Complying with various characteristics of unsteadiness, appropriate wing shapes and wing kinematics of flapping wings can be beneficial in optimizing the generation and enhancement of lift and thrust performance.

Table 1.1. Flapping biosystem's characteristic overview.

Items	**Insects**	**Humming Bird**	**Bat**	**Small Birds**	**Large Birds**	**Flapping MAV**	**Small Low Speed Airplanes**
1. Types	Beetles, Bumblebees, Butterflies, Dragonflies	Amazilia	Plecotus Auritus	Sparrows, Swifts, Robins	Eagle, Hawk, Vulture, Falcon, Skua Gull	DARPA DRO (Ho et al, 2003)	Cessna 210
2. Weight Typical (gf)*	25×10^{-5} - 12.8	5.1	9.0	35 - 82	952-4300	≤ 50	1045000
3. Wing Semi-span (cm)*	0.062 – 7.7	5.9	11.5	20 - 48	58-102	< 7.5	5600
4. Wing-Loading (g/cm^2)	10^{-3} – 10^{-1}	0.4	0.072	0.029-0.152	0.35 – 0.67	10^{-2} - 1	11.18
5. Typical Power (gf cm sec^{-1} per gf)	5.3 - 238	130	83	93 - 110	42 - 57	≈39	$\approx 1.3 \times 10^4$
6. Dominant Wing Movement	Hover	Hover and Fly	Fly	Fly	Fly	Hover and Fly	Fly
7. Flight Speed (m/s)	1.05 - 9	15	10 – 14	6 - 10	10 - 20	3-10	99m/s (cruise at 6100 m

							altitude)
8. Reynolds No.	10-1000	7500	14000	$10^3 – 10^4$	10^4 - 10^5	10^4 - 10^5	10,000,000
9. Leading Edge Vortex/LEV	LEV by swept wing at Re = 5×10^3	yes	Yes	yes	yes	yes	no
10. Entering its own TEV/ Wake Capture	yes	yes	No	no	no	no	no
11. Laminar Separation Bubble/LSB	yes	yes	Yes	yes	yes	yes	no
12. Leading Edge Flap	-	-	Has been observed on bats	-	e.g. Mallard, at Re = 6×10^4 (Jones et al, 2008) 	-	-
13. Self-activated flaps at TE					e.g. Skua Gull 		

*Power functions of wing dimensions and flight parameters against body mass, m, following Shyy (1999) and Norberg (1970). The exponent of correlation is for $(\text{Mass})^{\text{exponent}}$
(Source: Djojodihardjo et al, 2012, 2014)

1.2 Problem Statement/Formulation

"*Nature is the great master teacher*," in year 1966, Heinrich Hertel had written the phrase in his book of Structure-Form-Movement, illustrating the relation between biology and technology. It is essential to study the criteria, characteristic and constraints in order to comprehend how the mechanisms, principles and natural design are aerodynamically achieved in terms of technological applications. The nature and engineering structures usually display the same mechanical laws, such as for strength, stability, and high performance. For example, there may be the idea that flapping wing propulsion is more effective than propellers, since birds have gone through millions of years for adaptation to the surrounding and they use flapping mechanism, not propellers. Principally, ideal ornithopter mechanization has not yet been achieved due to the complex kinematical and aerodynamical characteristics of insects and birds, and there are many things that still need to be well-understood before integrating it within the system. For example, the way of flight widely differs for each flying creatures in achieving successful flight, even among animals that are operational within the same range of Reynolds number (Mueller, 2001).

In an attempt to serve the purpose of mechanization simplification for aerodynamic performance measure, aerodynamic modelling is introduced to provide a mathematical scheme that resembles biosystem characteristics and mechanics to describe the aerodynamic physics, without oversimplification and/or complexity of computation. The progression of aerodynamic modelling is derived from first principles, with introduction of simplifications to the fundamental equations on fluid mechanics reasoned by the relevant aerodynamics, geometric and kinematic considerations (Ansari, 2006).

There are several computational modellings that were developed to represent the aerodynamics of flapping wing such as strip theory, panel method, vortex lattice method and so on. Since the major emphasis is on simplicity, the chosen approach should offer relatively fast and least effort in computation with conveniences of any correction introduction, yet sufficiently accurate and reliable in assessing and providing desired aerodynamic performance (Weis-Fogh, 1973).

Strip theory is inspired from blade element theory which is known to be used in solving rotary wing problems. The theory has been utilized for flapping wing analysis by DeLaurier (1993), and also introduced by Shyy (2008), Azuma (2006) in their works. It is a simple tool that can provide adequate results without the complexity of computational methods (Harmon, 2008). In addition to its simplicity, strip theory presents the advantage of easily allowing for corrections, including semi-empirical stall models (Leishmann & Beddoes, 1989), and steady viscous drag (Murua et al, 2012). It is also very effective and applicable in designing and predicting the performance of flapping wing mechanization (Kim et al, 2008).

Motivated by aforementioned observations and overviews, the hypotheses of present study are as stated below;

i. Flapping biosystem can be modelled by simple pitching and flapping ornithopter.
ii. An optimum configuration which at least can represent the flapping biosystem, can be formulated by using parametric study.
iii. By utilizing parametric study and comprehensive assessment into the flapping mechanism, a better but simple system can be formulated, that will be unique as an entity.

Following the hypotheses, the research questions are addressed;

i. What is the important parameter in flapping system?
ii. Which one can be selected to represent a workable or viable model?
iii. What are the influences of each parameter on the performance?
iv. What is the synthesized flapping system configuration as the result of the present study?

With these hypotheses and research questions, the present work focuses on developing a physically and biologically based mathematical model to represent flapping wing biosystem that can easily be built into flapping wing ornithopter.

1.3 Objective

The primary objectives of the present work are to:

i. establish relevant parameters as related to physical conditions and producing desired characteristics of flapping wing biosystem.
ii. find the relationship between the relevant operating variables and design parameters of the conceived models.
iii. propose a physio-mathematical model which is modified strip theory that has been verified to give desired aerodynamic performance and can be easily built for flapping wing ornithopter.

1.4. Scope and Limitations

The present work is devoted to inviscid aerodynamic first order analysis but taken into account for viscous effect and higher order effects offered by more sophisticated approaches. Computational fluid dynamics (CFD) will be utilized for simulation and validation purposes. The CFD analysis is beyond the scope of the study. More sophisticated aerodynamic theories and analysis will be the subject of future work. CFD simulation results can be utilized for establishing insights and validation.

1.5 Thesis Outline

As such to convey a comprehensive and clear view throughout the subsequent chapters, composing of seven chapters, each chapter is briefly described below;

Chapter one offers a background of flapping wing ornithopter through observation by learning from nature behaviour. The flying biosystem is explored to gain the insight for the characteristics scheme of flapping system. The challenges and constraints faced are noticed to be tackled with designated analytical approach to solve stated problems and satisfy the objectives of the research.

Chapter two provides an overview of avian flight history and their impact in the aeronautical field. Variety of ornithopter platforms designs and related aerodynamic research are introduced and detailed as summary of previous analytical and experimental flight and aerodynamics research. Characteristic of biosystem is elaborated to provide an insight for wing configuration consideration.

Chapter three reviews a relevant aerodynamic theory used to develop the aerodynamic modelling structure, including aerodynamics for fixed wing, strip theory, and unsteady aerodynamic mechanisms. Each one is addressed accordingly to explain the significance in oscillating (flapping) wing flight phenomena for utilization in modeling formulation.

Chapter four details a generic aerodynamics of flapping wing theoretical development developed using theories and formulations described in previous chapter. Approach using modified unsteady aerodynamic strip theory, and chosen parameters and formulations are addressed to be calculated and analysed with certain kinematics of the wing. Finally, the aerodynamic expressions used to calculate forces are presented.

Chapter five demonstrates a basic computational analysis for two-dimensional flow visualization that serves for qualitative and quantitative investigation purpose. The details of performed analysis are elaborated explicitly with certain assigned simplifications.

Chapter six offers a results of the aerodynamic modelling when calculated and analyzed with particular specifications and parameters. Comparison of results with existing theoretical and experimental results from other works by researchers is carried out. Further investigation is then conducted by performing parametric study and establishing component-wise contribution of generic motion on the lift and thrust forces. The modelling is applied to bi-wing and quad-wing configurations. Assessment drawn to check relevant capability and reasons for argument are presented.

Chapter seven delivers a thesis summary and present general research conclusions with recommendations for more detailed and advanced, future work in the field.

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