

**INVESTIGATION OF TRANSLATIONAL AND
ROTATIONAL MOTION INDUCED FLOW
PATTERNS IN FLAPPING WING
AERODYNAMICS**

BINOY B



DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

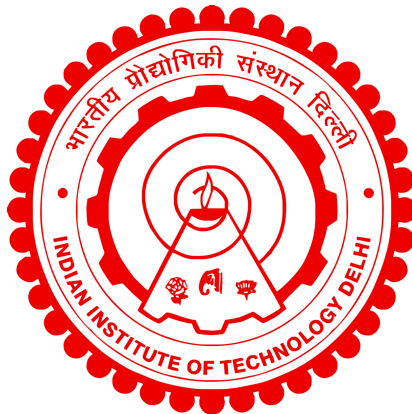
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Department of Mechanical Engineering

Submitted

in partial fulfillment of the requirements of the degree of Doctor of Philosophy

to the



**INDIAN INSTITUTE OF TECHNOLOGY
DELHI**

JULY, 2025

I would like to dedicate this thesis to my loving family...

Certificate

This is to certify that the thesis entitled “**Investigation of Translational and Rotational Motion Induced Flow Patterns in Flapping Wing Aerodynamics**”, submitted by **Mr. Binoy B** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a record of the original, bonafide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

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Binoy B.

Abstract

Flapping wings have significant importance in the field of micro aerial vehicles (MAVs). MAVs are capable of performing operations such as environmental monitoring, surveillance, and assessment in highly defended areas. Flapping Wing Micro Aerial Vehicles (FWMAVs) with particularly hovering capability are especially significant in military applications because flapping-wing flight offers a power-efficient and highly maneuverable basis for MAV design especially under low Reynolds number operating conditions, when compared to rotary-wing and fixed-wing UAVs. Further, fixed-wing UAVs are not capable of hovering, while rotary-type UAVs, although capable of hovering, are less efficient because of their small rotor size. While compared to military and transport aircraft, these micro aerial vehicles operate in the low Reynolds number regime of 10^5 or lower. It is evident that the main aerodynamic parameters, like a lift-to-drag ratio, considerably vary between the low and high Reynolds numbers and the aerodynamics associated with flapping wings are unsteady. The interplay between flapping wing kinematics and dimensionless parameters such as Reynolds numbers and reduced frequency also plays an important role in the performances of the micro-aerial vehicle. Motivated by the hummingbird figure-of-eight pattern wing kinematics during hovering conditions, we studied the influence of kinematics parameters such as frequency, stroke amplitude, pitch amplitude, and plunge amplitude by using force measurement and smoke flow visualization. The optimum wing kinematic conditions are identified by using surrogate modeling techniques. We designed and built an adjustable flapping wing mechanism with brushless DC servo motors with active and passive pitch types. This flapping wing mechanism can produce a figure-of-eight pattern. The experiment results show that a higher frequency of flapping leads to a higher value of force production, but it also results in a greater magnitude of negative force. The production of force positively correlates with the stroke amplitude, and larger amplitudes improve aerodynamic performance. The plunge amplitude varies non linearly with the output force, peaking at intermediate plunge amplitudes around 18° in the active pitch mechanism; similarly, the higher pitch amplitudes enhance force production at higher frequency. The optimal combination of higher frequency with increased pitch and stroke amplitudes with moderate plunge amplitude gives optimum force output. An important observation is that frequency and plunge amplitude are more

significant than stroke and pitch amplitude in lift generation. Additionally, the active pitch flapping mechanism produced higher forces compared to the passive pitch mechanism. Flow visualization showed a formation of vortices. Vortices, especially leading-edge vortices significantly enhance lift by generating low-pressure regions above the wing. This phenomenon is critical in unsteady flows, which enables high angles of attack without stall. Moreover the trailing edge vortices interact with LEVs to maintain circulation and stabilize the vortex system that contribute to the sustained lift. Additionally, wake capture phenomenon, where wings interact with the previously shed vortices, further enhance the lift.

Overall, we optimized the kinematic wing parameters for maximum lift force production. This hummingbird-inspired study to understand the influence of wing frequency, stroke amplitude, pitch amplitude, and plunge amplitude can lead to the development of next-generation flapping wing unmanned aerial vehicles with higher aerodynamic efficiency.

सारांश

फ्लैपिंग विंग्स का माइक्रो एरियल व्हीकल्स (MAVs) के क्षेत्र में महत्वपूर्ण स्थान है। MAVs का उपयोग पर्यावरणीय निगरानी, गुप्तचर कार्य और अत्यधिक संरक्षित क्षेत्रों में आकलन जैसी गतिविधियों में किया जा सकता है। विशेष रूप से हॉवरिंग (स्थिर उड़ान) में सक्षम फ्लैपिंग विंग माइक्रो एरियल व्हीकल्स (FWMVs) सैन्य अनुप्रयोगों में अत्यंत उपयोगी सिद्ध होते हैं, क्योंकि फ्लैपिंग-विंग उड़ान प्रणाली ऊर्जा-कुशल और अत्यधिक चपल होती है, विशेषकर जब इनका संचालन निम्न रेनॉल्ड्स संख्या की स्थिति में होता है। इसकी तुलना में, फिक्स्ड-विंग UAVs हॉवर नहीं कर सकते, जबकि रोटरी-विंग UAVs यद्यपि हॉवर कर सकते हैं, परंतु छोटे रोटर आकार के कारण वे कम दक्ष होते हैं।

सैन्य एवं परिवहन विमानों की तुलना में, ये माइक्रो एरियल व्हीकल्स 10^5 या उससे भी कम रेनॉल्ड्स संख्या की सीमा में कार्य करते हैं। यह स्पष्ट है कि मुख्य वायुगतिकीय पैरामीटर जैसे कि लिफ्ट-टू-ड्रैग अनुपात, निम्न और उच्च रेनॉल्ड्स संख्याओं के बीच काफी भिन्न होते हैं, और फ्लैपिंग विंग्स से जुड़ी वायुगतिकी पूर्णतः अस्थिर (unsteady) प्रकृति की होती है। फ्लैपिंग विंग की गतिशीलता और रेनॉल्ड्स संख्या एवं रेक्यूड फ्रिक्वेंसी जैसे विमाहीन मापदंडों के मध्य संबंध, माइक्रो एरियल व्हीकल के प्रदर्शन में महत्वपूर्ण भूमिका निभाते हैं।

हमने हॉवरिंग के दौरान हमिंगबर्ड द्वारा अपनाए जाने वाले आकृति-आठ (figure-of-eight) पैटर्न से प्रेरित होकर एक अध्ययन किया, जिसमें विंग काइनेमैटिक्स जैसे कि फ्लैपिंग फ्रीक्वेंसी, स्ट्रोक एम्प्लिट्यूड, पिच एम्प्लिट्यूड एवं प्लंज एम्प्लिट्यूड का प्रभाव बल उत्पादन पर मापा गया।

हमने एक समायोज्य फ्लैपिंग विंग मैकेनिज्म डिजाइन एवं निर्मित किया जिसमें ब्रशलेस डीसी सर्वो मोटर का प्रयोग किया गया तथा सक्रिय (active) एवं निष्क्रिय (passive) पिचिंग प्रकारों को शामिल किया गया। यह मैकेनिज्म आकृति-आठ पैटर्न उत्पन्न करने में सक्षम है।

प्रयोग से प्राप्त परिणामों में यह पाया गया कि फ्लैपिंग फ्रीक्वेंसी जितनी अधिक होती है, उतना ही अधिक बल उत्पन्न होता है, लेकिन साथ ही ऋणात्मक बल का मान भी बढ़ता है। स्ट्रोक एम्प्लिट्यूड में वृद्धि से बल उत्पादन में सकारात्मक प्रभाव देखा गया, जिससे वायुगतिकीय प्रदर्शन बेहतर हुआ।

प्लंज एम्प्लिट्यूड का बल उत्पादन के साथ अरेखीय (nonlinear) संबंध पाया गया, जिसमें सक्रिय पिच मैकेनिज्म के लिए लगभग 18° के मध्यमान पर अधिकतम बल प्राप्त हुआ। उच्च पिच एम्प्लिट्यूड्स भी अधिक फ्रीक्वेंसी पर

बल उत्पादन में सहायक सिद्ध हुए। फ्लैपिंग फ्रीक्वेंसी और प्लंज एम्प्लिट्यूड लिफ्ट जनरेशन में स्ट्रोक एवं पिच एम्प्लिट्यूड की तुलना में अधिक प्रभावशाली मापदंड पाए गए।

सक्रिय पिच मैकेनिज्म से निष्क्रिय पिच की तुलना में अधिक बल उत्पन्न हुआ। फ्लो विज़ुअलाइज़ेशन से यह स्पष्ट हुआ कि विंग के चारों ओर वॉर्टिसेस (vortices) का निर्माण होता है। विशेष रूप से लीडिंग-एज वॉर्टेक्स (LEV) ऊपरी सतह पर निम्न दाब क्षेत्र उत्पन्न कर लिफ्ट को बढ़ाते हैं। यह अनस्टेडी फ्लो स्थितियों में अत्यधिक सहायक होता है, जहाँ स्टॉल के बिना उच्च एंगल ऑफ अटैक प्राप्त किया जा सकता है।

इसके अतिरिक्त, ट्रेलिंग-एज वॉर्टिसेस (TEV) LEV के साथ अंतःक्रिया करके वायुगतिकीय परिसंचरण (circulation) को बनाए रखते हैं, जिससे वॉर्टेक्स प्रणाली स्थिर रहती है और स्थिर लिफ्ट का निर्माण होता है। वेक कैप्चर की घटना, जिसमें पंख पूर्व में उत्पन्न वॉर्टिसेस के साथ पुनः संपर्क करता है, लिफ्ट को और बढ़ाता है।

अंततः, हमने बल उत्पादन को अधिकतम करने के लिए विंग काइनेमैटिक्स के मानों का अनुकूलन किया। हमिंग-गबर्ड से प्रेरित यह अध्ययन यह दर्शाता है कि फ्लैपिंग फ्रीक्वेंसी, स्ट्रोक एम्प्लिट्यूड, पिच एम्प्लिट्यूड और प्लंज एम्प्लिट्यूड जैसे मानदंडों का फ्लैपिंग-विंग UAVs के वायुगतिकीय प्रदर्शन पर गहरा प्रभाव है। यह अध्ययन भविष्य में उच्च दक्षता वाली अगली पीढ़ी की फ्लैपिंग विंग UAVs के विकास की दिशा में मार्गदर्शन प्रदान करता है।

Contents

Certificate	i
Acknowledgements	ii
Abstract	iii
Contents	vi
List of Figures	x
List of Tables	xii
Nomenclature	xiii
1 INTRODUCTION	1
1.1 Background	1
1.2 Motivation	4
1.3 Objectives	5
1.4 Outline of the thesis	6
2 LITERATURE REVIEW	8
2.1 Introduction	8
2.2 Unsteady Aerodynamics in flapping flight	8
2.2.1 Leading-Edge Vortex	9
2.2.2 Tip Vortices	10
2.2.3 Pitch-Up rotation	11
2.2.4 Wake capture occurs	11
2.2.5 Clap and Fling Mechanism	13
2.3 Influence of wing shape	14
2.4 Wing kinematics	16
2.5 Flapping wing mechanism	18

2.6	Force measurement and flow visualization	23
2.7	Surrogate modelling	25
2.8	Conclusions from the literature review	29
3	METHODOLOGY	31
3.1	Scaling law	32
3.1.1	Reynolds number (Re)	32
3.1.2	Reduced frequency (k)	33
3.1.3	Wing kinematics	33
3.1.4	Design and fabrication of wings	35
3.2	Design and Fabrication of flapping mechanism	38
3.2.1	Introduction	38
3.3	Design	39
3.3.1	Fabrication	42
3.4	Prototype:1	43
3.5	Prototype:2	45
3.6	Prototype:3	47
3.7	Design of Experiments(DOE)	48
3.8	Surrogate Modeling	50
3.8.1	Surrogate Modeling Overview	51
3.8.2	Polynomial Regression (PR)	51
3.8.3	Kriging Model	52
3.8.4	Evaluation Metrics	54
3.8.4.1	Prediction Error Sum of Squares (PRESS)	54
3.8.4.2	Relative TPR (Total Prediction Error Ratio)	55
3.9	Conclusion	55
4	Force Measurement and Analysis	57
4.1	Introduction	57
4.2	Experimental Setup	58
4.3	Apparatus/Hardware	58
4.4	Data acquisition systems	60
4.5	High speed Camera	61
4.6	Connections	61
4.7	Pre-Testing Conditions	62
4.8	Uncertainty and error analysis	63
4.9	Qualitative analysis of figure-of-eight motion generation	65
4.10	Force measurement and analysis	66
4.11	Experimental Results	67
4.11.1	Active pitch mechanism	67
4.11.2	Comparison of elliptical wings-different scale ratio	71
4.11.3	Comparison of rectangular with elliptical wing	73

4.11.4	Passive pitch mechanism	74
4.12	Surrogate model	77
4.13	Heat Map	79
4.14	Conclusion	81
5	Smoke Visualization	82
5.1	Introduction	82
5.1.1	Experiment 1	82
5.1.2	Experiment 2	84
5.1.3	Experiment 3	86
5.2	Conclusions	88
6	Conclusions and Scope for Future Work	90
6.1	Conclusions	90
7	Suggestions for Future Work	93
	Bibliography	95
	List of Publications and Patent	112

List of Figures

1.1	Sketches of human powered flying machines with flapping wings by Leonardo da Vinci [1].	2
1.2	Different types of micro aerial vehicle (a) fixed-wing.[4], (b) rotary-wing[5], and (c) flapping wing [6].	3
1.3	(a) & (b) figure-of-eight motion of hummingbird wings in hovering.[8].	4
2.1	Leading edge vortex [18].	10
2.2	LEVs of Hawkmoth and Fruit fly[19].	10
2.3	A–F depicts a wing section as it reverses stroke, the wing interacts with its previous wake.[26].	12
2.4	Clap-and-fling mechanism (a–d) section schematic of wings approaching each other to clap, (a–d) fling apart.[32].	13
3.1	Flapping wing kinematic parameters [68].	35
3.2	Figure-of-eight pattern using Lissajous curve.	35
3.3	Pitch angle variation.	35
3.4	Wings with ID (a) 1:1:1 (b) 2:1:1 (c) 1:1:2 (d) 2:1:2.	37
3.5	Rufous Hummingbird wing.	38
3.6	Three-axis motion [1].	38
3.7	CAD model of flapping wing mechanism.	40
3.8	Wingtip trajectory (a) to (d) one cycle, divided into four parts, (e) and (f) one complete cycle	41
3.9	CAD model of prototpe:1.	43
3.10	Flapping mechanism.	43
3.11	Detailed View:1.Servo-1,2.Servo-2,3.Servo-3,4.Wing,5.Wing coupler,6.Servo-1 Coupler,7.Sevo-2,coupler 8.Servo-3 coupler.	44
3.12	Vertiq BLDC Servo Motor.	45
3.13	Isometric view of the flapping mechanism prototype:2, (a) Side view, (b) Front view, (c) Top view.	47
3.14	Passive Mechanism with elliptical wing.	48
3.15	Passive mechanism with rectangular wing.	48
3.16	Surrogate Modelling Process.	50
3.17	Implementation of Kriging Model	54

4.1	Experimental setup.	59
4.2	ME F6D45 Torque Sensor.	59
4.3	Arduino Mega 2560.	62
4.4	(a) Measured mean forces, (b) Reference 1-gram weight	65
4.5	Wing motion path tracking (a)Plunge amplitude 2° , (b)Plunge amplitude 24°	66
4.6	FFT of (a) raw net force and (b) inertial force.	68
4.7	Unfiltered force (a) net force and (b) inertial force.	68
4.8	Filtered force (a) net force and (b) inertial force.	69
4.9	Force (a) The filtered net and inertial force and (b) Lift force.	69
4.10	Comparison of lift forces with (a) frequencies 3Hz and 6Hz, (b) stroke amplitude 40° and 80° , (c) pitch amplitude 30° and 180° , (d) plunge amplitude 2° and 24° , and (e) plunge amplitude 13° and 24°	70
4.11	Comparison of lift forces for elliptical wing with different scale ratio (a) frequency 6Hz, (b) frequency 3Hz, (c) stroke amplitude 80° , (d) pitch amplitude 30° , (e) Plunge amplitude 24°	72
4.12	Comparison of lift forces for elliptical and rectangular wing (a) frequency 3Hz, (b) stroke amplitude 80° , (c) pitch amplitude 30° , (d) Plunge amplitude 24°	74
4.13	Comparison of Lift forces with (a) frequencies 3.5 Hz and 6Hz, (b) stroke amplitude 40° and 120° and (c) plunge amplitude 2° and 24°	75
4.14	Contour plots of maximum lift forces with kinematic parameters in active pitch	78
4.15	Contour plots of maximum lift forces with kinematic parameters in passive pitch.	79
4.16	Heat map for (a) Active Pitch mechanism (b) Passive Pitch mechanism.	80
5.1	Smoke visualization frames showing the evolution of span-wise vortices, figures (a)–(h) correspond to sequential time steps.	84
5.2	Smoke visualization frames showing the evolution of chord-wise vortices, figures (a)–(h) correspond to sequential time steps.	86
5.3	Smoke visualization frames showing the wake capture mechanism, figures (a)–(h) correspond to sequential time steps.	88

List of Tables

2.1	Summary of various flapping wing mechanisms and their contributions.	19
2.2	Various Surrogate Techniques.	27
3.1	The wing parameters of rufous hummingbird [124].	36
3.2	The wing Specifications.	37
3.3	Mechanical properties of the ABS, PLA and PETG materials.	42
3.4	The EMAX ES9251 II micro servo motor.	43
3.5	Vertiq Motor specifications.	46
3.6	Flapping wing kinematic parameters.	49
3.7	Kinematic parameters maximum and minimum value.	50
4.1	Zero signals for each channel.	60
4.2	Calibration Matrix A	60

Nomenclature

Acronyms

ABS	Acrylonitrile butadiene styrene
ANN	Artificial Neural Network
AoA	Angle of attack
BLDC	Brushless DC electric motor
CAD	Computer-aided design
DOE	Design of experiments
DOF	Degree of freedom
DPIV	Digital particle image velocimetry
ESC	Electronic speed controller
FDM	Fused deposition modeling
FPS	Frame per second
FWMAV	Flapping wing micro air vehicle
GP	Gaussian process
LEV	Leading edge vortex
LHS	Latin hypercube sampling
MAV	Micro air vehicle
PETG	Polyethylene Terephthalate Glycol
PIV	Particle image velocimetry
PLA	Polylactide
PR	Polynomial regression
PRESS	Prediction error sum of squares
PWM	Pulse width modulation
RPM	Revolutions per minute

RTEV	Rotational trailing-edge vortex
SFPM	Spatial four-point motion
TEC	Trailing edge control
TEV	Trailing edge vortex
TiV	Tip vortex
TPR	Total prediction error ratio
UAV	Unmanned air vehicle

Symbols

α	Pitch angle
β	Plunge angle
ν	Kinematic viscosity
ω	Angular frequency of the wing
ϕ	Stroke angle
AR	Aspect ratio
b	Wing span
f	Flapping frequency
F_y	Span wise force
F_z	Normal force
GND	Ground
k	Reduced frequency
L_{ref}	Wing chord length
M_x	Moment about x axis
M_y	Moment about y axis
M_z	Moment about z axis
R	Wing semi span
Re	Reynolds number
Rx	Receive pin
S	Wing area
Tx	Transmit pin
U_{ref}	Wing tip velocity