INVESTIGATION OF AERODYNAMICS OF BIOINSPIRED FLAPPING WINGS

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DECLARATION

I declare that this is my own work and this Dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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The supervisors should certify the Dissertation with the following declaration.

The above candidate has carried out research for the Master of Philosophy Dissertation under our supervision. We confirm that the declaration made above by the student is true and correct.

Name of Supervisor: Dr. K.K.N.M.P. Samaraweera

Signature of the Supervisor: Date: 07/04/2025

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Signature of the Supervisor: Date: 07/04/2025

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Signature of the Supervisor: Date: 07/04/2025

DEDICATION

To free education,
To fellow Sri Lankans whose generosity facilitates it,
And,
To the heroes whose sacrifices keep it alive.

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ABSTRACT

In the quest to develop bioinspired micro air vehicles capable of efficient operation in dynamic environments, transient measurements of aerodynamic forces on pitching and plunging wings are essential. While previous investigations have measured these forces, there remain gaps in knowledge that impede further development of bioinspired micro air vehicles. Overarching characteristics of lift and thrust performances of pitching and plunging wings in varying kinematic scenarios have not been the subject of extensive research. The majority of previous research has concentrated on assessing the performance of custom-developed wing platforms tailored for specific flapping wing micro air vehicle applications. In cases where a standard airfoil shape is employed, investigations have been limited to a few wing flapping frequencies or free-stream velocities. In this research, unsteady aerodynamic forces of pitching and plunging wings in a range of frequencies and free stream velocities inspired by birds are investigated both experimentally and computationally.

The experimental investigation encompasses fourteen different kinematic scenarios spanning Reynolds numbers from 20,000 to 100,000 and Strouhal numbers from 0.02 to 0.1. Complementing this, the computational investigation provides additional insights through time series variations in aerodynamic forces, velocity, and pressure contour for twenty-five kinematic scenarios, including those examined experimentally. The range of Reynolds and Strouhal numbers is derived from measurements taken from birds in forward flapping flight. An experimental apparatus, purposefully designed and developed for this investigation, is used in subjecting a wing with a uniform cross-section of the NACA 0012 airfoil to controlled pitch and plunge motions while simultaneously measuring the aerodynamic forces acting on the wing. The measurements taken using a force sensor are post-processed to compute the time-history variation of lift and thrust coefficients in varying kinematic scenarios. Characteristics of resultant lift and thrust coefficient variations and average values are discussed with existing findings in flapping wing aerodynamics. Gradual decrements of extremum values in transient lift and thrust coefficient variations are observed with increasing Reynolds number and receding Strouhal number values. The mean values of lift and thrust coefficients increase by an average of 35% and 83% respectively with increasing Strouhal number in Reynolds number values of 20 000 and 40 000. But the mean lift coefficient values decrease by an average of 46% with rising Reynolds number while Strouhal number is 0.02 and 0.04. Results indicate that flapping wing micro air vehicles perform efficiently in Reynolds numbers below 40 000 with stability in forward accelerations and altitude changes increasing with rising Reynolds number values.

The computational investigation was done using Ansys fluent computational fluid dynamics simulation software. After establishing an optimized simulation methodology, a series of simulations were carried out. Aerodynamic force values are exported and postprocessed to develop velocity and pressure contour plots as images and animations to further supplement the experimental and computational results. The characteristic trends observed in the experimental results were confirmed by the computational results. The mean lift coefficient values exhibit an average increase of 31% with rising Strouhal number values, while they decrease by an average of 54% with increasing Reynolds number values. On the other hand, the mean thrust coefficient values demonstrate an average increase of 32% with increasing St values and a rise of 11% on average with increasing Reynolds number values. The comparison between experimental and computational results reveals a favorable agreement in the time-history variations of lift and thrust coefficients. The percentile deviation between the mean lift and thrust coefficients of the experimental and computational results is calculated at 12.15%, indicating a reasonably close correlation.

Keywords: Experimental Aerodynamics, Computational Fluid Dynamics, Bioinspired Wings, Micro Air Vehicles, Flapping Wings

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF APPENDICES

NOMENCLATURE

δ	Measurement uncertainty
$\dot{q}$	Energy generation per unit volume
μ	Dynamic viscosity
μ_k	Turbulent eddy viscosity
ν	Kinematic viscosity
$\boldsymbol{V}$	Velocity vector field
ρ	Air density
σ	Percentile uncertainty
σ_k	Turbulent Prandtl number
τ	Shear stress
c	Chord length
C_D	Drag coefficient
C_L	Lift coefficient
e	Specific internal energy
f	Body force per unit mass
F_D	Drag force
F_L	Lift force
f_x	External force
$F_{P/C}$	Force measurement perpendicular/ parallel to the wing chord
g	Gravitational acceleration
I	Identity matrix
K	Reduced frequency
k_T	Thermal conductivity

l Span length

m, n Calibration coefficients

P Fluid pressure

Re Reynolds number

St Strouhal number

T Temperature

T_n Normalized periodic time

U, V, W Fluid velocity

$V_{P/C}$ Voltage measurement perpendicular/ parallel to the wing chord

LIST OF ABBREVIATIONS

UAV	Unmanned Aerial Vehicle
BAV	Bioinspired Aerial Vehicle
MAV	Micro Aerial Vehicle
FWBAV	Flapping Wing Bioinspired Aerial Vehicle
FWBMAV	Flapping Wing Bioinspired Micro Aerial Vehicle
CFD	Computational Fluid Dynamics
PIV	Particle Image Velocimetry
UPM	Unsteady Panel Method
FVM	Finite Volume Method
LES	Large Eddy Simulation
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
CNC	Computer Numerical Control
AIAA	American Institute of Aeronautics and Astronautics
AGARD	Advisory Group for Aerospace Research and Development
NATO	North Atlantic Treaty Organization
AoA	Angle of attack
LEV	Leading Edge Vortex
TEV	Trailing Edge Vortex

LIST OF PUBLICATIONS

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