Modeling of Ground Effect Benefits for Multi-Rotor Small Unmanned Aerial Systems at Hover

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Abstract

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Modeling of Ground Effect Benefits for Multi-Rotor Small Unmanned Aerial Systems at Hover (12 pp.)

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Small Unmanned Aerial Systems (sUAS) are gaining prevalence in both the public and private sectors. A proximity induced phenomenon that produces aerodynamic perturbations as a result of increased thrust production called Ground Effect (GE) poses a challenge to stable flight for aircraft flying close to the ground. GE has been previously examined for full-scale manned helicopters, but the effect upon multi-rotor Vertical Take-Off and Landing sUAS requires further investigation. Existing aerodynamic analysis methods such as Blade Element Momentum Theory (BEMT) have not considered GE. A Ground Effect modified BEMT power prediction method based around the modification of coefficient of thrust was developed herein. Thrust data for a multi-rotor sUAS propeller within GE at select power settings and distances was collected for comparison with the results of the GE BEMT thrust prediction developed. The thrust prediction method was adapted to model power requirements for multi-rotor sUAS at hover within GE. Finally, flight testing of a multi-rotor sUAS was conducted to evaluate the results of the GE BEMT model. The GE BEMT thrust prediction method was found to predict thrust with an average difference of 2.3% from experimental thrust data. The experimental power requirement for the multi-rotor sUAS tested was reduced by more than 26% within GE. The adaptable GE BEMT model developed was shown to predict power required for a multi-rotor sUAS vehicle at hover within GE.

To my parents

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a	Previous or Initial Axial Induction Factor (-)
A	Rotor Disk Area (m^2)
a_{new}	Current Axial Induction Factor (-)
b	Tangential Induction Factor (-)
b_{new}	Current Tangential Induction Factor (-)
c	Chord (m)
c_d	Coefficient of Drag (-)
c_l	Coefficient of Lift (-)
c_{p_r}	Coefficient of Power Required (W)
c_t	Coefficient of Thrust (-)
c_{t_r}	Coefficient of Thrust Ratio (-)
$c_t(z)$	Coefficient of Thrust with Modification for GE (-)
c_q	Coefficient of Torque (-)
c_{q_r}	Coefficient of Torque (-)
D	Rotor Diameter (m)
dD	Differential Drag from Blade Element Theory (N)
dL	Differential Lift from Blade Element Theory (N)
dr	Size of Span-Wise Element (m)
dT_b	Differential Thrust from Blade Element Theory (N)
dT_m	Differential Thrust from Momentum Theory (N)
dT_n	Span-Wise Element Thrust (N)
dQ_b	Differential Torque from Blade Element Theory (N-m)
dQ_m	Differential Torque from Momentum Theory (N-m)
dQ_n	Span-Wise Element Torque (N-m)
g	Acceleration Due to Gravity (m/s^2)
k	Induced Power Variation Inside Ground Effect (-)
k_∞	Induced Power Variation Outside Ground Effect (-)
L	Characteristic Length of Object (m)
m	Mass of Vehicle (kg)
$\dot{m}$	Mass Flow Rate of Air in Slip Stream (kg/s)
N	Number of Elements (-)
N_b	Number of Propeller Blades (-)
N_P	Number of Propellers (-)
P	Power (W)
P_d	Dynamic Pressure (kPa)
P_{IGE}	Power Inside Ground Effect (W)
P_{OGE}	Power Onside Ground Effect (W)
P_{SP}	Total Power Required for Single Propeller (W)
P_{TR}	Total Power Required (W)
Q	Total Torque (N-m)

Q_R	Torque Required (N-m)
r	Radial Distance of Element from Hub (m)
R	Rotor Radius (m)
R_{e_L}	Reynolds Number (-)
T	Total Thrust (N)
TI	Turbulence Intensity (-)
T_{IGE}	Thrust Inside Ground Effect (N)
T_{OGE}	Thrust Outside Ground Effect (N)
T_{RH}	Thrust Required to Hover (N)
TSR	Tip Speed Ratio (-)
T_{SP}	Thrust Required from Single Propeller(N)
$\bar{U}$	Average of Time Series Flow Velocity (m/s)
V	Air Velocity (m/s)
V_0	Axial Induced Velocity Component (m/s)
V_2	Tangential Induced Velocity Component (m/s)
V_∞	Axial Slip Stream Velocity (m/s)
V_{OUT}	Voltage Output (V)
V_i	Induced Velocity (m/s)
V_{loc}	Local Induced Velocity (m/s)
V_r	Tangential Slip Stream Velocity (m/s)
V_S	Voltage Supplied (V)
w	Slip Stream Velocity Far Beneath Rotor (m/s)
W	Vehicle Weight (N)
z	Vertical Height of Propeller from Ground (m)

α	Angle of Attack (rad)
ϵ_a	Axial Induction Factor Error (-)
ϵ_b	Tangential Induction Factor Error (-)
η_m	Motor Efficiency (-)
θ	Pitch (rad)
λ_i	Inflow Ratio (-)
μ	Advance Ratio (-)
μ_∞	Viscosity of Fluid (m^2/s)
ρ	Air Density (kg/m^3)
ρ_∞	Free-Stream Air Density (kg/m^3)
σ	Standard Deviation of Time Series Flow Velocity (m/s)
ϕ	Inflow Angle (rad)
Ω	Propeller Rotational Speed (rad/s)
Ω_R	Propeller Rotational Speed Required(rad/s)

List of Acronyms

AoA	Angle of Attack
BEMT	Blade Element Momentum Theory
BET	Blade Element Theory
CW	Clockwise
CCW	Counter-Clockwise
DAQ	Data Acquisition
ESC	Electronic Speed Controller
GE	Ground Effect
IGE	Inside Ground Effect
IMU	Inertial Measurement Unit
Li-Po	Lithium-Polymer
LPE	Local Position Estimate
MAV	Micro Air Vehicle
MT	Momentum Theory
NI	National Instruments
OGE	Outside Ground Effect
PWM	Pulse-Width Modulation
sUAS	Small Unmanned Aerial System
TSR	Tip Speed Ratio
UAS	Unmanned Aerial System
VTOL	Vertical Take-off and Landing

1 Introduction

1.1 Motivation and Problem Statement

Unmanned Aerial Vehicles (UAVs) are powerful robotics tools used by both military and civilian communities alike. Advances in lightweight materials and commercial electronics have increase the range, payload, and reliability of the crafts. Reduced costs have brought the technology to a wide range of communities which have found uses such as surveillance, reconnaissance, and aerial photography to name a few. As the complexity of the tasks increase, the complexity of the guidance and control systems increase as well. Traditionally, guidance and control laws have been regarded as separate systems responsible for independent tasks. Potential field and vector field methods have blurred the line between guidance and control systems, whereas now they have shared the burden of complex tasks such as obstacle avoidance and path following. Potential field has been effective for obstacle avoidance and goal seeking for a singular discrete point, however is not initially intended to be used for tasks such as path following. Vector field methods have been effective at providing guidance and control for fixed wing UAVs for converging to and following a path. Vector fields can be constructed in a number of ways, however a convenient method first introduced in constructs a field by summing together three components consisting of convergence, circulation, and time varying. The filed is generated by calculating the integral lines converging to and following the level sets of intersecting arbitrary surfaces in n-dimensions. Unlike potential field, vector fields do not take into account the dynamics of a vehicle being provided the guidance which provides no guarantee that the UAV will avoid obstacles. Improving the guidance provided by the vector field for obstacle avoidance may be possible by modifying the circulation term of a vector field as a function of a vehicles state with respect to the obstacle.