Modeling Quadrotor Propeller Thrust near Structures

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Introduction

Small quadrotors are highly maneuverable vertical take-off vehicles that have potential for autonomous inspection of buildings, bridges, dams, boilers and refineries and other infrastructure. Quadrotor maneuvers are possible by varying the relative thrust produced by the four rotors.

- Modeling thrust of a quadrotor propeller is necessary for control under wind gusts and ground effects.
- An accurate, yet computationally efficient, semi-empirical model of quadrotor propeller aerodynamics near structures is required.
- Propeller thrust model will be incorporated in a quadrotor controller to make real-time decisions in autonomous inspection missions.

Figure 1: DJI Inspire 1 quadrotor that will be used in this study. *Photo Credit:*

Figure 2: Autonomous quadrotor for inspections.
*Photo Credit:https://cdn-images-1.medium.com/max/1920/1*6mh3wsOnepwk7HT_zBgYyg.jpeg*

Problem Statement

Motivation: Manual inspections of bridges, boilers, and dams is time consuming and expensive, and it usually requires construction of interior and exterior scaffolding. Autonomous quadrotor inspections bypass these requirements and are, therefore, a better alternative.

Challenge: Quadrotors hovering close to a structure can experience wind gusts, ground effects and other aerodynamic disturbances. These aerodynamics are usually not included in quadrotor thrust models to avoid complex computations in online decision-making. Therefore, a low or medium fidelity thrust model of these aerodynamics is desired.

Literature Review

- Thrust produced in hover conditions is modeled using momentum theory[1].
- Semi-empirical models of ground effect for rotors depend on the distance from the ground [2,3].
- A dynamic model of the quadrotor incorporating induced drag and rotor blade flapping is available in the Robotics Toolbox for MATLAB and Simulink [4].
- Vortex panel methods have been used to predict unsteady aerodynamics for lifting bodies [5].

Gaps in Literature: Most quadrotor thrust models do not incorporate aerodynamic disturbances due to ground/wall effects and rotor blade flapping.

Contribution

A medium fidelity thrust model that incorporates ground effects, propeller aerodynamic properties and thrust variations due to blade flapping and induced drag.

Modeling Ground Effect in Hover

Ground/Wall Effects refer to the aerodynamic influence of a structure (wall, ground or other obstacle) that can disturb the quadrotor's motion and interfere with the mission.

Simple 2D model of ground effects - Method of Images

- *Simulating a boundary:* Airflow near a boundary effect can be modeled by superimposing the velocity potential of a point source and its image using potential flow theory. The straight streamline shared by both the point objects can be considered as the boundary and the flows on each half-plane can be treated separately.

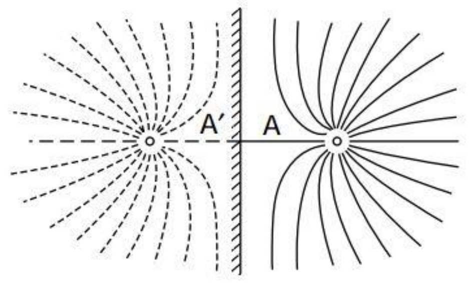

Figure 3:Potential flow model for velocity surrounding a point source and its image; the straight streamline becomes a boundary [6]

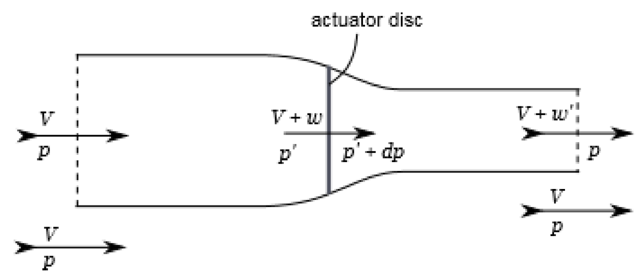

Figure 4: Flow through a propeller according to momentum-disk theory

- The rotor disk is model as a line source and its image is given by a line source of equal strength placed at the certain distance from the boundary.
- The thrust on the rotor is calculated as the net momentum difference across a control volume surrounding the rotor.

Semi-empirical Ground Effect Model

- The thrust ratio in ground effect and outside ground effect varies with height of quadrotor from ground.
- A semi-empirical model for ground effect is given by [3]:

$$\frac{T_{OGE}}{T_{IGE}} = 1 - \rho\left(\frac{R}{4h}\right)^2$$

T_{OGE} : Thrust required for hover outside ground effect
T_{IGE} : Thrust required for hover in ground effect
h: Height of the motor from the ground
R: Radius of the rotor shaft
ρ: Experimentally determined coefficient

Comparing Potential Flow Model to Ground Effect Model

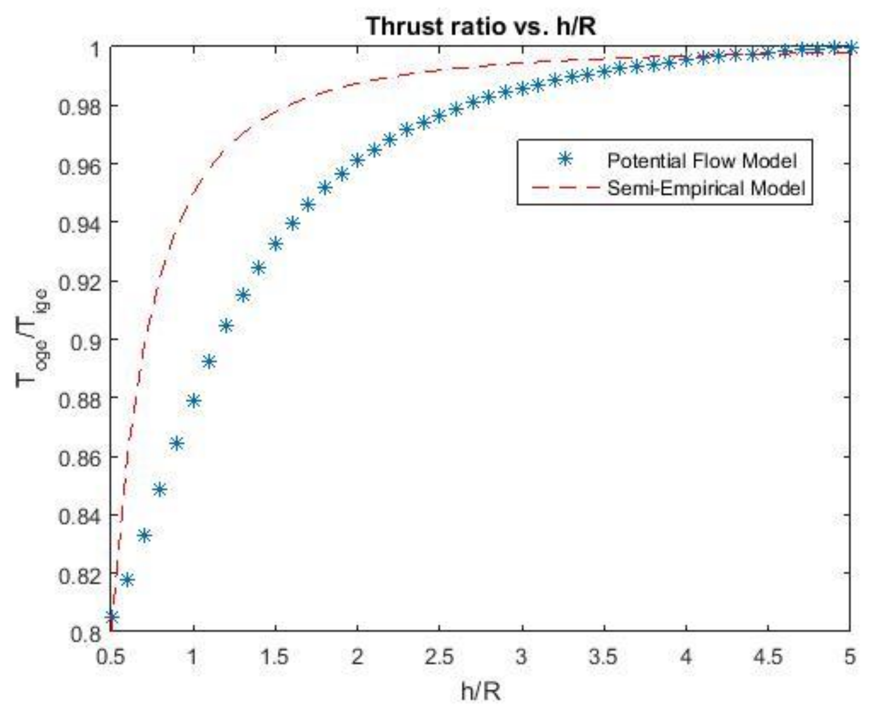

Figure 5: Comparing potential flow model with the semi-empirical ground effect model [3]

The potential flow model of hover in ground effect qualitatively matches the empirical model from literature.

Vortex Panel Methods

- Panel Method is used to find the surface lift distribution of the quadrotor propeller
- Based on potential flow and calculates the circulation density at each control point
- Velocity parallel to the panel is calculated from circulation density
- Requires geometric modeling of the propeller to design the panels on the propeller surface

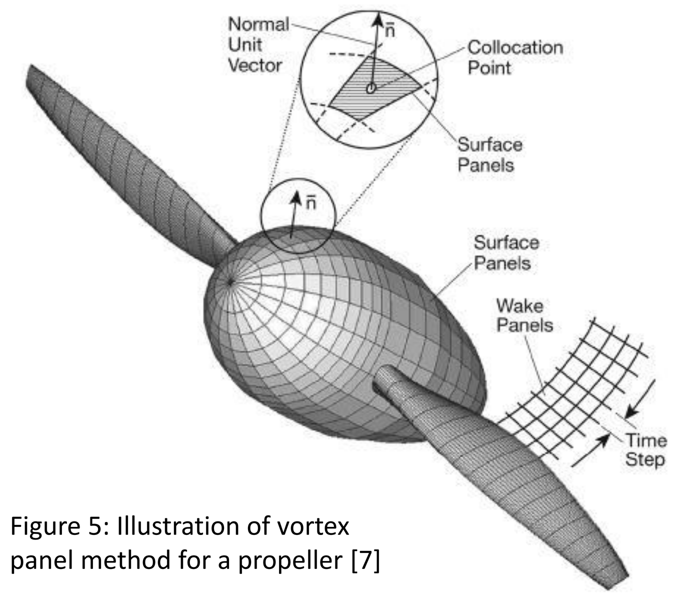

Figure 5: Illustration of vortex panel method for a propeller [7]

Vortex Panel Method for a 2D Airfoil

- Vortex Panel method code written in MATLAB for thin NACA airfoils
- Airfoil contour is approximated using vortex panels of linearly varying strength [5].

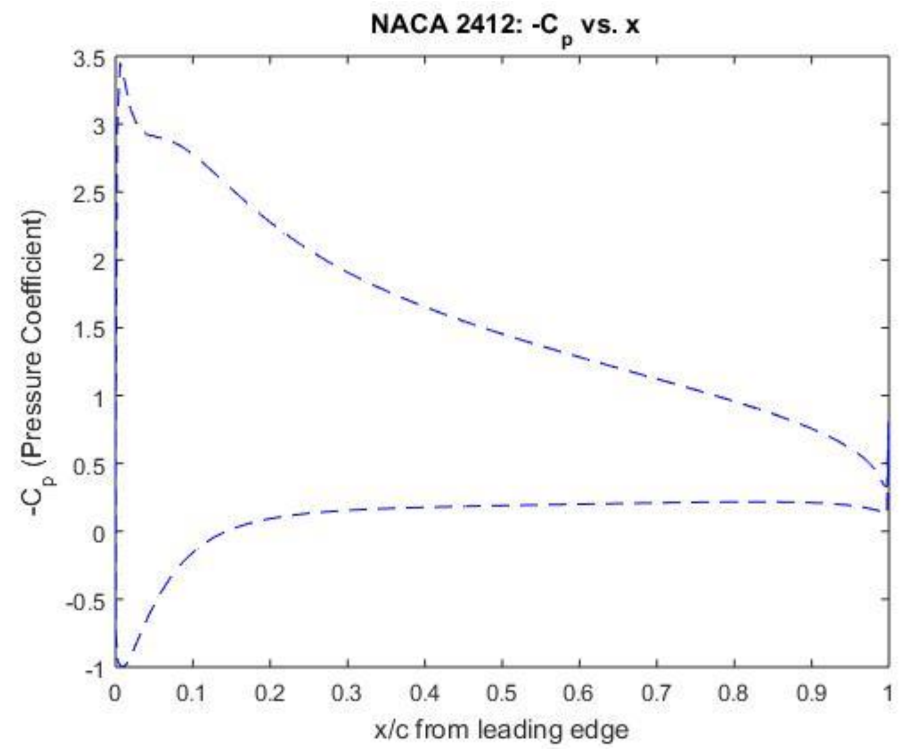

Figure 6: Pressure coefficient vs. normalized x-location along airfoil chord.

Panel method simulations for 2D airfoils agree with results available in literature [5].

Future Work

- Develop vortex panel method code for propellers of finite span
- Integrate ground effect model and rotor blade flapping with the vortex model
- Incorporate the thrust model into the Simulink model of the quadrotor controller
- Conduct experiments to test the quadrotor control algorithm

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