ANALYZING THE CEILING EFFECT ON UAV THRUST VARIATIONS THROUGH COMPUTATIONAL AND EXPERIMENTAL STUDIES

Joud N. Satme[1], Ryan Yount[1], Spencer Schwartz[1], Austin R.J. Downey[1,2], Yue Ling[1]

[1]Department of Mechanical Engineering, University of South Carolina, Columbia, USA
[2]Department of Civil and Environmental Engineering, University of South Carolina, Columbia, USA

ABSTRACT

The ceiling effect influences UAV performance by increasing rotor thrust when operating close to overhead structures. This phenomenon poses challenges for UAV-based sensor deployment, particularly in structural health monitoring (SHM) applications, where precise and safe sensor placement is crucial. Understanding how the ceiling effect alters aerodynamic forces is critical for optimizing UAV control strategies in such environments. Previous research has investigated the ground effect on UAVs, but studies on ceiling effects remain limited. Prior work primarily relies on empirical testing, lacking comprehensive modeling to distinguish aerodynamic changes due to propeller proximity from other environmental variables. These gaps highlight the need for a detailed experimental and computational approach to quantify the ceiling effect. This study examines the phenomenon through computational fluid dynamics (CFD) simulations and experimental testing to analyze thrust variations at different ceiling distances. A controlled test setup measures thrust, power draw, and RPM, while high-fidelity CFD simulations capture airflow behavior and pressure distributions. Findings reveal a nonlinear increase in thrust as the ceiling distance decreases, aligning with aerodynamic predictions. A polynomial model is developed to integrate ceiling effect corrections into UAV control algorithms. These results provide a framework for adaptive flight controllers that compensate for ceiling-induced thrust changes, improving UAV stability in constrained environments.

Keywords: ceiling effect, sensor deployment, UAV system, computational fluid dynamics

1. INTRODUCTION

In the aftermath of natural disasters and man-made emergencies, it is crucial to assess damage states in critical civil infrastructure. Extreme weather conditions and environmental factors often cause structures to be inaccessible or dangerous to inspect for manned operations. Traditionally, structural health monitoring (SHM) also requires substantial time and equipment commitments by on-site crews.

Unpiloted Aerial Vehicles (UAVs) offer a safer, more efficient solution by avoiding the need for human operators to directly interact with potentially unstable or challenging structures. UAVs equipped with Electro-Permanent Magnets (EPMs) can enhance this deployment for SHM sensors by facilitating remote sensor placement. The integration for EPMs allows for secure attachment and detachment of sensor packages to and from structures, mitigating risks, time consumption, and equipment allocation associated with manual deployment.

The motivation behind the experiment and Computational Fluid Dynamics (CFD) simulations is to develop a ceiling effect controller that enhances the safety and efficiency of UAV pilots when deploying sensor packages. By understanding and integrating the ceiling effect dynamics, the controller would provide UAV pilots with more precise and reliable control.

The ceiling effect presents challenges in the deployment of sensor packages with UAVs. The occurrence of the ceiling effect happens when UAVs operate close to structural ceilings, unintentionally increasing rotor thrust due to altered airflow patterns.

The research aims to answer the following question: How can the ceiling effect on UAV thrust be characterized and compensated for to enhance stability during sensor deployment in SHM?

The contributions of this work are twofold. First, it quantitatively characterizes the ceiling effect on UAV thrust through a combination of controlled experiments and high-fidelity CFD simulations, establishing a nonlinear relationship between ceiling proximity and thrust augmentation. Second, it lays the foundation for a predictive flight controller by proposing a polynomial model to compensate for thrust variations caused by close proximity to a ceiling. This enhances UAV stability in constrained environments, particularly during sensor deployment for structural health monitoring.

2. METHODOLOGY

This work involved a detailed review of the aerodynamic behavior of UAV propellers, particularly under high angles of incidence, as investigated by Yuchen Leng et al. [1]. Their experimental analysis utilized a wind tunnel to measure forces and moments

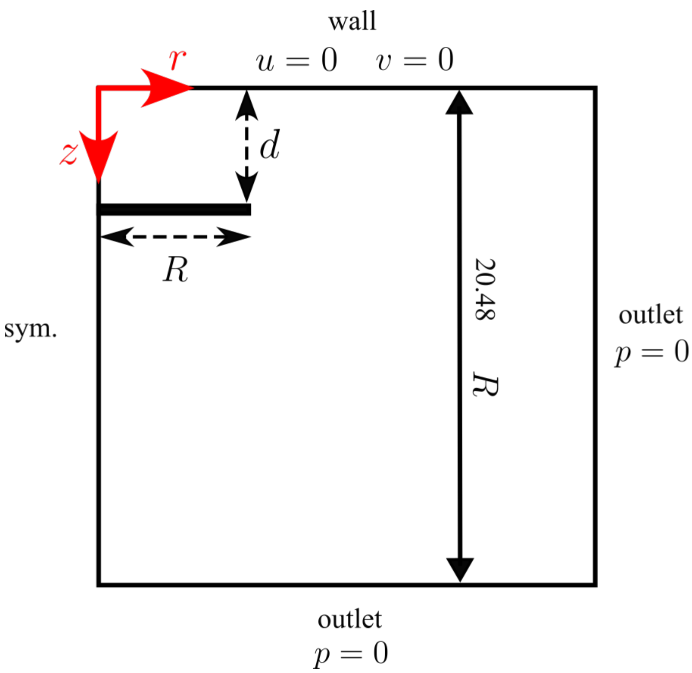

FIGURE 1: DIAGRAM OF THE SIMULATION DOMAIN, WHERE *d* AND *R* DENOTE THE DISTANCE TO THE CEILING AND THE PROPELLER RADIUS, RESPECTIVELY. THE LEFT BOUNDARY IS THE AXIS OF SYMMETRY, AND THE TOP BOUNDARY REPRESENTS THE NO-SLIP CEILING WALL.

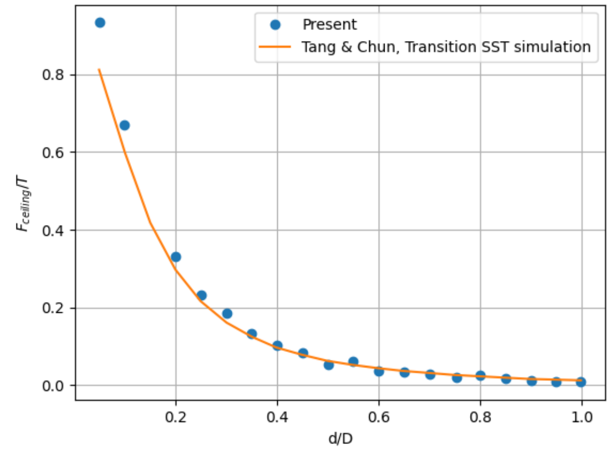

FIGURE 2: CEILING FORCES AS A FUNCTION OF d/D.

on propellers, highlighting the role of three-dimensional effects and stall delay on propeller performance. Additionally, Eraslan et al.'s comprehensive analysis of quadrotor UAV propeller performance was examined, focusing on propeller and thrust coefficients, which was useful in determining what to investigate in this project [2].

This study further explored the influence of proximity to surfaces on UAV flight efficiency. The framework proposed by Gao et al. for exploiting ground and ceiling effects for energy-efficient UAV motion planning without additional sensors was analyzed, demonstrating potential energy savings [3]. Research by Paz et al. on the ground effect through CFD analysis provided insights into the aerodynamic stability of multirotor systems near walls and the ground, supporting the idea of the development of more stable flight control systems exploiting the ground and ceiling effects [4].

The methodology also included a review of advancements in flight controllers and aerodynamic models for stable control under varying environmental conditions. The study by Tang et al. on the ceiling effect's impact on drone-scale propellers and the experimental validation of ceiling effects on rotor aerodynamics by Nakanishi et al. were useful in understanding the adjustments needed in UAV flight control systems for improved stability [5, 6]. Research on stable control methods for UAVs flying under ceilings and the demonstration of reduced power usage through the ceiling effect on small rotorcraft further emphasized the potential of aerodynamic principles in enhancing UAV flight efficiency [7, 8].

2.1. Modeling and Simulation

In this section the procedure of simulating the propeller under the ceiling effect is covered along with the governing equations.

The disk actuator model is employed to simulate the flow induced by the propeller and its interaction with the ceiling. In this approach, the propeller is modeled as an infinitely thin disk of radius R, with a pressure jump Δp across the disk, computed from the thrust T as

$$\Delta p = \frac{T}{A}, \tag{1}$$

where $A = \pi R^2$ is the disk's surface area, and T is assumed constant. By neglecting rotational flow over the propeller blades, the disk actuator model significantly reduces computational cost. Nonetheless, as shown in previous studies [5], it adequately captures large-scale flow features and the propeller-ceiling interaction.

The disk actuator model is implemented in the open-source solver *Basilisk* [9, 10]. *Basilisk* employs a finite-volume approach, using a projection method to enforce incompressibility. The resulting pressure Poisson equation is solved via a multigrid method. The constant pressure jump across the disk is enforced by applying Δp to cell faces after solving the pressure equation. Consequently, when the velocity is corrected using the modified ∇p, cells on either side of the disk experience the desired pressure gradient. In this study, a pressure jump of $\Delta p = -1$ is used. The time step is governed by a CFL number set to 0.5.

Given the axisymmetric nature of the flow induced by the disk actuator, a two-dimensional simulation is performed. A key dimensionless parameter is the Reynolds number, defined as $\mathrm{Re} = UD/\nu$, and set to 1,000 in this study. Tests with higher Re and Δp values confirmed that key conclusions regarding the ceiling effect remain unchanged.

Parametric simulations systematically explore the effect of ceiling distance by varying d/D from 0.05 to 1, where $D = 2R$. The domain size is set to $[20.48R \times 20.48R]$, as shown in Figure 1. This large domain mitigates spurious pressure field noise from outlets positioned too near the propeller. The right and bottom

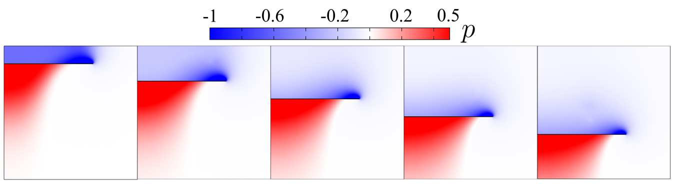

FIGURE 3: PRESSURE FIELDS RESULTS FOR d/D = 0.1, 0.2, 0.3, 0.4, AND 0.5 (LEFT TO RIGHT) IN DISK ACTUATOR SIMULATIONS

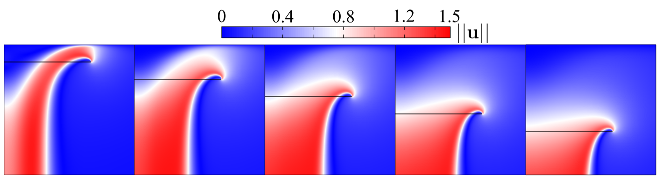

FIGURE 4: VELOCITY MAGNITUDE FIELD RESULTS FOR d/D = 0.1, 0.2, 0.3, 0.4, AND 0.5 (LEFT TO RIGHT) IN DISK ACTUATOR SIMULATIONS, WITH A COLOR SCALE FROM 0 TO 1.5.

boundaries are pressure outlets, while the top surface is a no-slip ceiling wall. An adaptive quadtree mesh discretizes the domain, enabling dynamic refinement in user-defined regions. The minimum cell size is $h_{\text{min}} = 0.00125$, corresponding to $R/h_{\text{min}} = 800$, or 800 cells across the propeller radius. This resolution suffices to resolve the smallest gap considered (d/D = 0.05), providing approximately 80 cells within the gap.

Following [5], we integrate the pressure p over the ceiling to compute the total force as

$$F_{\text{ceiling}} = 2\pi \int p \cdot r \, dr, \tag{2}$$

which quantifies the ceiling effect on propeller thrust. After an initial transient phase, F_{ceiling} reaches a quasi-steady state, and its time-averaged value is measured for various d/D. Results, shown in Figure 2, align well with [5] and confirm a thrust gain from the ceiling effect. The effect diminishes for $d/D > 0.8$, with F_{ceiling} decaying approximately exponentially.

Pressure and velocity fields for five d/D values are presented in Figures 3 and 4. At $d/D = 0.1$, the pressure above the propeller is significantly lower than in other cases, driving a larger F_{ceiling}. The velocity magnitude near the propeller increases as d/D decreases, creating a low-pressure region via the Bernoulli effect, thus enhancing thrust. Consequently, the most significant thrust gain occurs at $d/D = 0.05$, where the gap is smallest.

2.2. Experimentation

In this experiment, the influence of the ceiling effect is investigated. Using an aluminum frame, a propeller is placed in the center with an actuated ceiling placed over it. The ceiling had a travel distance of 2.5-25 cm. This allowed for precise control over the ceiling height and a constant speed during the ceiling travel, simulating a UAV approaching a structure. A data acquisition system is set up to measure load (propeller thrust), distance from the ceiling, motor power consumption, and RPM under various degrees of ceiling effect as indicated in Figure 5. The anticipated thrust vs. ceiling effect curve is demonstrated by simulations shown in Figure 2.

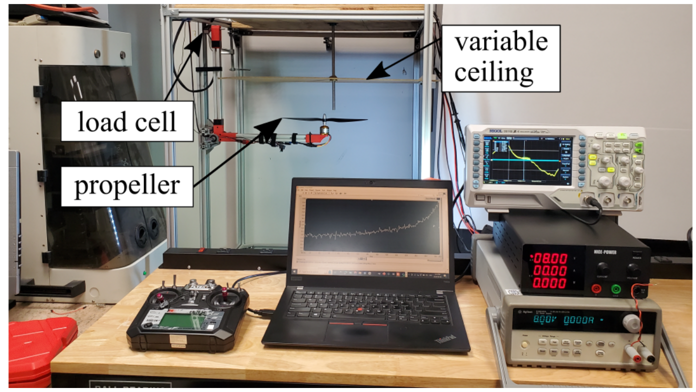

FIGURE 5: TEST SETUP FOR THE VARIABLE CEILING EFFECT EXPERIMENT WITH KEY COMPONENTS ANNOTATED.

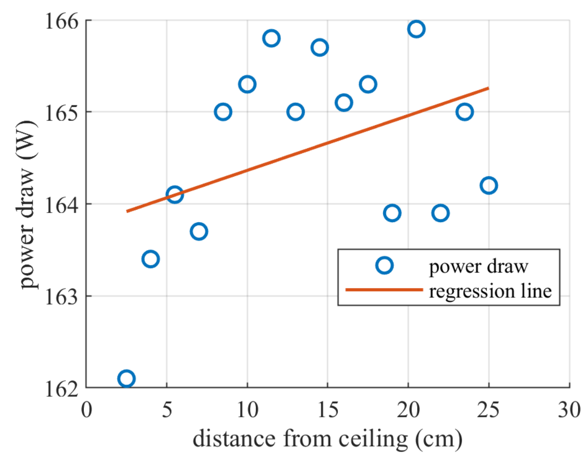

FIGURE 6: POWER DRAW OVER VARIABLE CEILING DISTANCE.

3. RESULTS AND DISCUSSION

During the test examining power draw with variable ceiling distance, the results showed minimal variation in power consumption. The power draw, shown in Figure 6, remained relatively stable, ranging from a low of 162 W at the beginning of the test to a peak of 165.8 W.

The results designed to examine the power draw of the propeller under varying ceiling conditions are illustrated in Figure 6. The figure includes experimental data points taken from the average power draw at each distance.

The analysis of the power draw under varying ceiling effects revealed low differences across all cases. The largest difference from the overall mean occurred at 15.24 cm, where the observed average was only 0.46 W higher. Additionally, the highest variation in standard deviation was 0.40 at 10.16 cm, demonstrating a stable power draw across all tests as indicated in Table 1.

As shown in Figure 7, the thrust force was measured experimentally across varying ceiling distances. The results exhibit a clear decaying trend as the ceiling moves farther from the propeller, indicating an inverse relationship between ceiling-induced

TABLE 1: TEST DISTANCE VS. POWER DRAW STATISTICS

Test distance (cm)	Power draw (W)	Standard deviation
15.24	165.19	1.45
10.16	164.99	1.69
5.08	164.50	1.15
3.81	164.86	1.53
2.54	164.51	1.20
Open	164.31	0.89

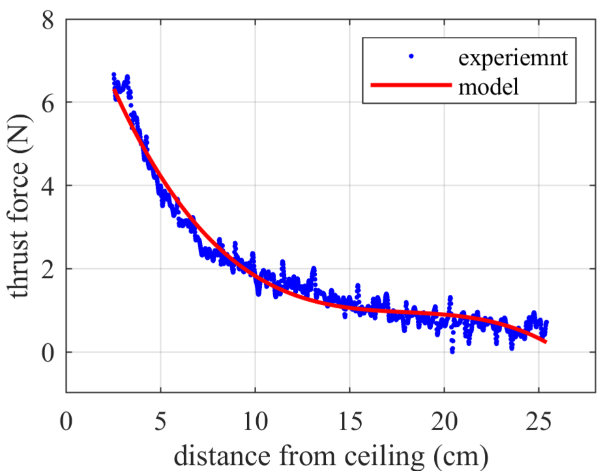

FIGURE 7: POLYNOMIAL MODEL FIT TO THE VARIABLE CEILING EXPERIMENTAL DATA.

thrust and the propeller's distance from the ceiling. This observed behavior aligns with aerodynamic expectations and is further validated by the CFD simulation results presented earlier in this work. To enable future implementation on a flight controller, a polynomial model is fitted to the experimental data, as shown in equation 3.

$$F(x) = -0.0014x^3 + 0.0734x^2 - 1.3435x + 9.28 \quad (3)$$

The model will aid in implementing a reliable ceiling effect controller where the thrust of propellers will be altered depending on the distance from the ceiling. This will attenuate the effect and increase the stability of the UAV sensor deployment system when navigating environments with impeded airflow.

The metrics presented in Table 2 indicate a strong fit between the proposed polynomial model and the experimental data. The high coefficient of determination ($R^2 = 0.97$) suggests that the model effectively captures the relationship between thrust force and distance from the ceiling. Additionally, the low root mean square error (RMSE) of 0.27 confirms the model's predictive accuracy, supporting its integration into control strategies for UAVs operating near overhead surfaces. This modeling approach sets the foundation for implementing a thrust-compensator module on the UAV flight controller, enabling stable operation in restrictive environments where the ceiling effect significantly impacts thrust dynamics.

TABLE 2: MODEL FIT METRICS

Metric	Value
R-square	0.9685
DFE	1439
RMSE	0.2661

4. CONCLUSION

This effort sets a framework for the future development of a ceiling effect controller to aid in the safe deployment of sensors onto civil infrastructure. CFD simulations, along with an experimental investigation, are covered in this work. This aims to deduce a relationship between the distance of a propeller from a ceiling and the induced additional thrust caused by the ceiling effect. The simulation results and experimental data have shown a high degree of correlation. Additionally, a model is derived that indicates an inverse relation between ceiling height and the induced thrust. The model, implemented on a flight controller, promises a high degree of stability under various degrees of ceiling effect, given the distance from that ceiling. This work will further enhance the reliability and safety of UAV-sensor deployment systems in structural health monitoring applications.

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