Force Modelling of Wall-Proximity Effect Induced by Ducted Quadrotor

Cheuk Chi Tsang, Peiwen Yang, Weisong Wen, *Member, IEEE*

***Abstract*—The increased use of unmanned aerial vehicles (UAV) in urban and indoor scenarios has necessitated the integration of propeller ducts due to safety concerns. We discovered the enhanced wall-proximity effects of ducted UAVs, demonstrating the suction force between the wall and the UAV. This article presents a force model of the wall-proximity effect that can be utilized to avoid collisions and navigate unknown obstacles. As the velocity of air between the vertical surface and the duct is higher than on the opposite side of the duct, a suction force acting towards the vertical surface is generated. This force depends on the mass flow rate of air between the duct and the vertical surface, distance, and a constant related to the shape of the duct. Experiments with a force sensor are conducted, measuring the force produced with various ducts installed, at different distances and different rotational speeds. Our model is validated through the linear relationship between the wall-proximity force and rotational speed, as well as the wall-proximity force and distance from the vertical surface. Finally, experimental data and videos are open-source and available to benefit further research at https://github.com/MclarenTsang/ducted_FM.**

***Index Terms*—Unmanned Aerial Vehicle (UAV), Wall-Proximity Effect, Ducted propellers, Force modelling, Interactive Safety.**

I. INTRODUCTION.

Unmanned aerial vehicles (UAVs), have increasingly been adopted for urban or indoor scenarios due to their agility and versatility. Current uses include construction [1], agriculture [2], and logistics [3,4]. Among all UAVs, quadrotors have been the most popular variant. This can be attributed to its ability to hover steadily and to operate in tight urban airspace. Ducted propellers have been proven to be able to assist in indoor navigation, due to the enhanced wall-proximity effect [5]. By integrating it into the control algorithm, the distance of a vertical surface in proximity can be estimated without visual feedback, mitigating collision risks. Therefore, ducted propellers show great potential in navigation and require further investigation.

With the increasingly frequent use of quadrotors in urban environments and confined airspace, safety has become a paramount concern. Even if scholars propose controllers with safety constraints such as robust model predictive control (MPC) [7,8], there is still a probability of collision occurrence. Although a model suggested that the probability of avoidance using MPC can be up to 89.99% [6], any UAV collisions often result in damage to propellers and rapid loss of flight ability. Further studies on TinyMPC show promise in implementing MPC on resource-constrained UAVs, however, results displayed a maximum position error of 23 cm [9]. This magnitude of error is likely to result in a collision in navigation of tight airspaces. Therefore, ducted UAVs can serve as the last barrier to avoid physical contact with the propeller.

Ducted rotors-based UAV demonstrates significant advantages in both safety and performance. Traditional quadrotors leave propellers exposed, making them vulnerable to entanglement with foreign objects such as strings or branches, which can snap the propellers, disrupt balance of lift, and lead to an imminent crash. Propeller ducts are a promising way to ensure the safety of the UAV in a collision, by providing a physical barrier against foreign objects. Ducts enclose the entire rotor system, allowing the possibility of stable flight to be regained after collisions, protecting people on the ground and the quadrotors themselves [10]. Beyond safety, advantages of ducts include greater thrust and reduced disturbance between propellers, improving propeller efficiency [11]. Furthermore, ducted propeller designs can mitigate noise by smoothing airflow and reducing propeller tip vortices [12]. With the noise of UAVs being a major concern for public acceptance of urban applications [13], ducts play into increasing urban applications of UAVs. However, the installation of duct alters the aerodynamic characteristic of UAVs. This study explores the underlying mechanism of these aerodynamic changes.

Existing aerodynamic model research on ducted UAVs mainly focuses on the aerodynamic modelling of thrust and optimization of duct design. For example, it is found that optimizing the design of a ducted single propeller led to an increase of 24.5% in lift force production, and even a 7.0% increase in lift force production in basic configuration [14]. However, there are fewer models of how ducted propellers impact flight stability and maneuverability when approaching walls. Moreover, there are more mentions of the ground effect and ceiling effect, typically on smaller UAV frames for indoor operation [15,16]. Compared to the wall-proximity effect, the ground effect on ducted UAVs has been studied more extensively. The ground effect leads to decreased duct thrust, but increased thrust of the blades, leading to a decrease in the efficiency of ducted fans [15]. While the ground effect pushes the UAV away from the horizontal surface below, the ceiling effect pulls the UAV towards the ceiling, which can lead to a collision in extreme cases [17]. On the other hand, staying close to the ceiling increases the rotor wake, leading to greater thrust [18]. Therefore, the system does not need to generate the same thrust when hovering, with the current drawn from the battery

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decreased significantly. However, in our experiment, we do not observe a significant increase in thrust.

The wall-proximity effect is less researched than the ceiling and ground effect. This is primarily due to the noise level caused by the propeller affecting the pressure sensor attached to the UAV, making it challenging to develop a precise model. Furthermore, the change in differential pressure is not as large as the ground effect, but a decrease in pressure can still be measured at a significant proximity from the wall [16]. Interestingly, when the ducted propeller approaches the wall, we discovered that a suction force is generated due to aerodynamic effects. Therefore, it is necessary to consider the impact of this suction force on system dynamics. The work [9] suggested that the tilting of the propeller causes the wall-proximity effect, but the reason for the propeller tilting was not explained. Therefore, we propose the suction force model according to the observation of smog direction and concentration. In addition, the suction strength of ducts with different shapes is explored. *With the implementation of the ducted propeller, when the UAV approaches a vertical surface, the established aerodynamic model can be applied for compensation control or aerodynamic interaction perception.* It is paramount that the aerodynamics of UAV ducts be fully modeled and implemented in control algorithms. This would also benefit further iterative designs in propeller ducts. Many previous studies have stated the wall-proximity effect of ducted propellers, but few have fully identified the cause of such an aerodynamic phenomenon.

Contributions: This paper specifically addresses the wall effect of ducted propellers through airflow visualization and empirical table-top experiments, eventually modelling the suction forces due to the wall-proximity effect. This is accomplished through force experiments involving a force sensor, analyzing the data that matches our proposed model.

Specifically, the main contributions of this paper include:

1) Proposing a force model and explanation for the wall-proximity effect through experimental data.
2) Investigating different curvatures in the structure of the duct that cause varying suction forces in the wall-proximity effect.
3) Analysing the effect of varying distance between vertical surface and duct and rotational speed of propeller on suction forces due to the wall-proximity effect.

The structure of the paper is as follows. In section II, the theory we proposed for the wall-proximity effect is explained. Section III introduces the tabletop experiments conducted, with the factors affecting the wall-proximity effect discussed through the results. In Section IV, a discussion of the possible uses of the force model is presented. Finally, the conclusion and future work are summarized in section V.

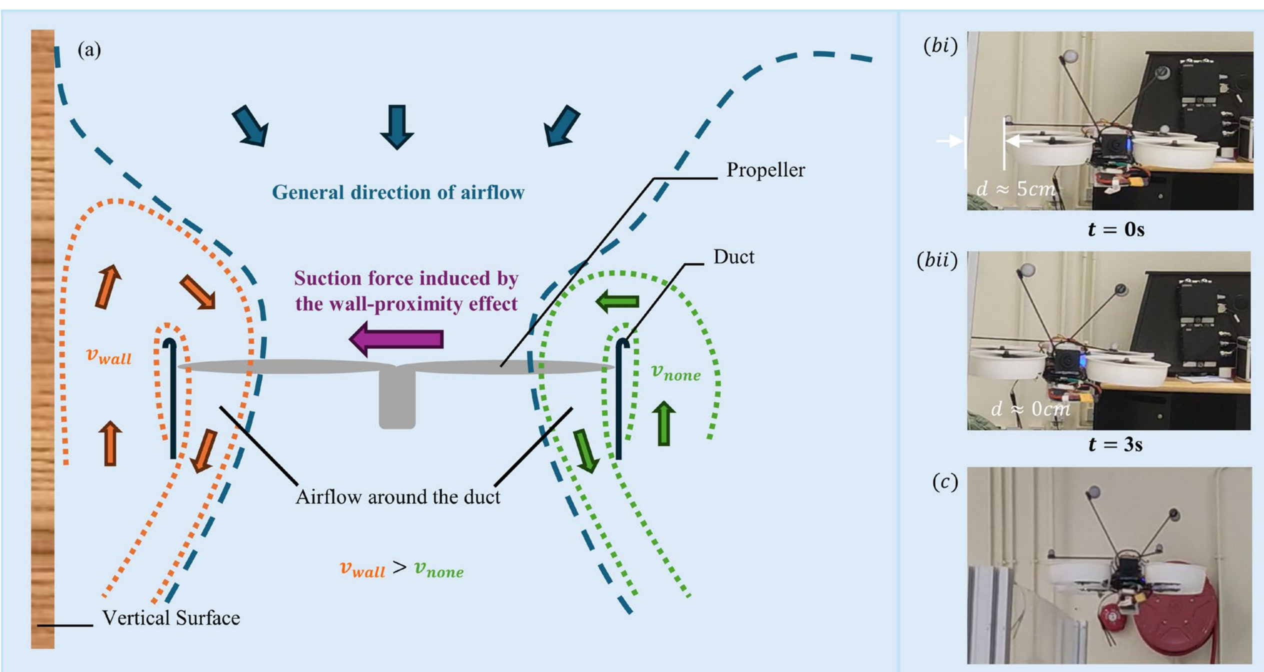

Fig. 1. Proposed theory for wall-proximity effect induced by ducted propellers. (a) A schematic drawing showing the airflow around the propeller duct when a ducted propeller is in the vicinity of a wall. (b) The initial hover experiment is to test for the wall-proximity effect, where the vertical surface is moved to vary the suction forces and to test the critical distance D_{max}. (c) A test with the quadrotor above the vertical surface, where there is no visible suction force acting on the quadrotor due to its proximity to the wall, removes the possibility that the airflow below the propellers is causing the wall-proximity effect. The video recording of the experiments can be found through the GitHub link.

II. THEORY

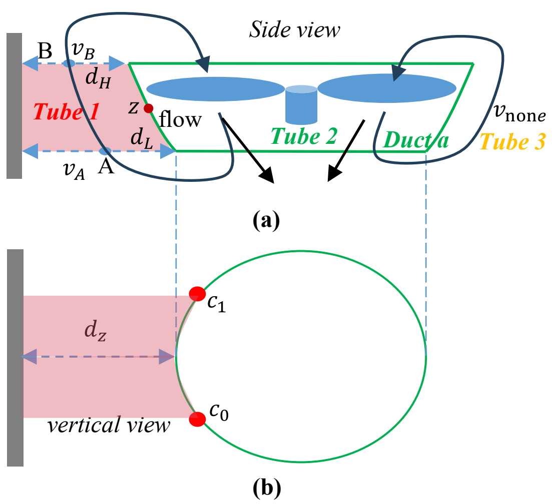

Fig 2. Take the curved duct as an example. (a) Side view. (b) Vertical view.

The upper circular area of different rotor ducts is the same, while the lower surface circular area has three types of areas that exhibit three different modes: vertical, outward turning, and inward turning. The model of three ducts is illustrated in Fig 3 (b).

Bernoulli's equation (BE) is the continuity equation for steady one-dimensional flow. The BE shows that the greater the area, the lower the velocity, and vice versa. This is precisely why air from a pipe rushes out at a greater velocity if the mouth of the pipe is pinched, thus decreasing the area of the cross-section. We use BE to analyze the force model of different ducts.

BE is as follows:

$$gz + \frac{p}{\rho} + \frac{v^2}{2} = \mathcal{L} \tag{1}$$

where gz is the potential energy per unit mass of fluid, p/ρ is the static pressure energy per unit mass of fluid, and $\frac{v^2}{2}$ is the kinetic energy per unit mass of fluid. The kinetic energy of a fluid with mass m and velocity v is $\frac{mv^2}{2}$. $\mathcal{L}$ is constant.

Observation: As shown in Fig 1 (a), the air spirals to the top of the propeller due to the presence of the outer duct. These experiments will be described in the following experiments section in detail.

Assumption 1: When the structurally determined duct approaches the wall vertically, the airflow volume V_I per unit time at entrance A is constant.

Therefore, based on assumption 1, the velocity v_z at any point of the duct's left surface with height z is as follows:

$$v_z = \frac{V_I}{\int_{c_0}^{c_1} d_z(c)\, dc} \tag{2}$$

where d_z represents the distance between any point c on the duct's surface and the wall, c_0 and c_1 represent the terminal point of tube 1.

Therefore, according to (1) and (2), the pressure p_z at any point of the duct's left surface with height z is as follows:

$$p_z = \left(\mathcal{L} - \left(\frac{V_I}{\int_{c_0}^{c_1} d_z\, dc}\right)^2 \Big/ 2\right)\rho \tag{3}$$

Then, the suction force of the duct's left surface is as follows:

$$\begin{aligned} F_l &= \int_{z_L}^{z_H} \int_{c_0}^{c_1} p_z\, dc\, dzdz \\ &= \int_{z_L}^{z_H} \int_{c_0}^{c_1} \left(\mathcal{L} - \left(\frac{V_I}{\int_{c_0}^{c_1} d_z\, dc}\right)^2 \Big/ 2\right)\rho\, dcdz \end{aligned} \tag{4}$$

where z_L and z_H represent the upper bound and low bound of the duct, respectively.

We can draw some conclusions from (4) that (a) If $d_z^a > d_z^b$, and suction force exists, for the same structural ducts, according to (4), $F_l(d_z^a) < F_l(d_z^b)$. This indicates that when ducts of the same shape are closer to the wall, the suction force increases. (b) For cases where ducts are far away from the wall, air cannot diffuse infinitely, therefore there must exist a d_{max} for all d_z, $d_z < d_{max}$. There is a minimum value of suction force $F_l(d_{max})$. Thus, when the duct is separated from the wall by a certain distance d_{max}, the pressure on both sides of the duct is balanced and the suction force is negligible. (c) If d_H is a constant, for all z, and $z_H \geq z \geq z_L$, corresponding distance d_{z_v}, d_{z_o}, d_{z_i} for vertical, outward turning, and inward turning, respectively, $F_l(d_{z_o}) < F_l(d_v) < F_l(d_i)$ due to $d_{z_o} < d_{z_v} < d_{z_i}$.

III. EXPERIMENTS

Initially, ducts were installed onto a UAV platform, with all four propellers of the quadrotor enclosed. *Flight experiments were conducted in an indoor environment, and the wall-proximity effect was investigated by moving a large vertical surface closer to the hovering quadrotor.* The control input signals can be programmed into the control board, then the electronic speed controller (ESC) can receive the control input signals to drive the propeller. At the same time, force data can be collected using the data interpreter connecting with a computer.

The suction force induced by the wall-proximity effect attracts the quadrotor toward the vertical surface, eventually colliding with the surface. A visible acceleration towards the vertical surface was observed. To prove the phenomenon and confirm our hypothesis, we have set up a tabletop experiment, as shown in Fig 3. Two sets of experiments were conducted, to prove and model the effect of shape and rotor speed would have on the suction forces with the vertical surface.

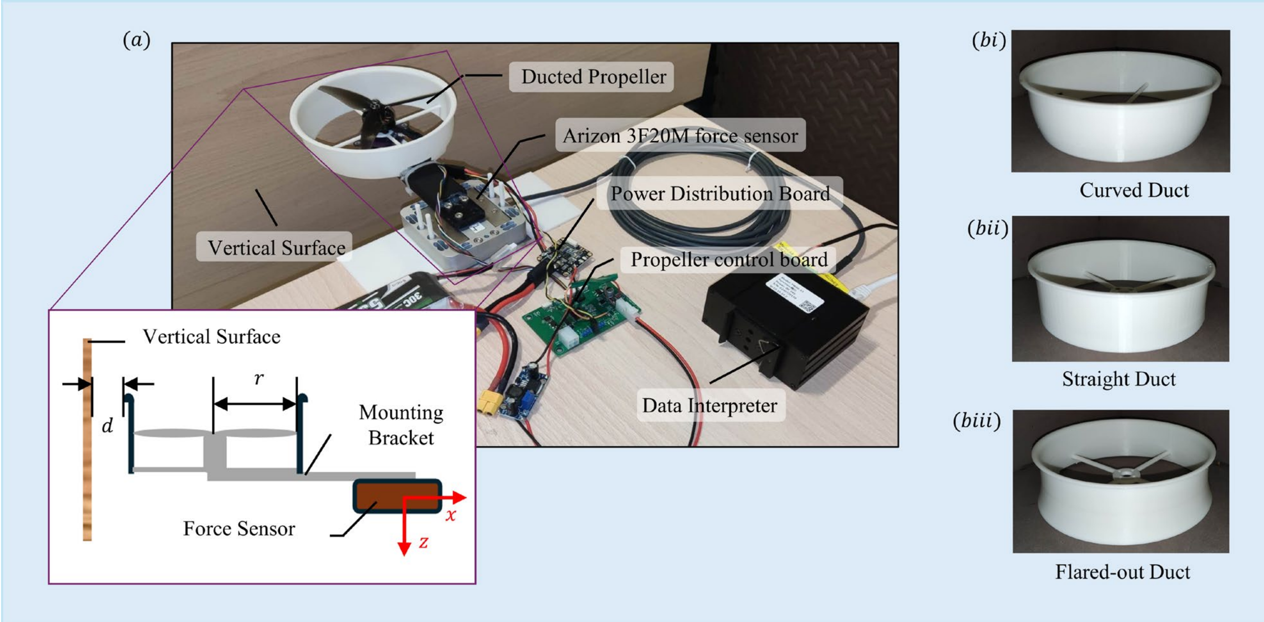

Fig 3. Overview of experimental setup. (a) A photo of the tabletop experimental setup used for force measurements. The ducted propeller is fixed onto the force sensor and mounted onto a solid tabletop surface. Different duct shapes, PWM values, and distances to the surface are tested. The inset shows a drawing of the setup from a side perspective, with $r = 63.5$ mm. (b) The three different designs of ducts are used to test their effect on the wall-proximity effect.

A. Investigating the effect of duct design and distance from vertical surface on the wall-proximity effect

Three UAV ducts have been designed to study the effect of the wall-proximity effect. All ducts feature a rounded lip of $r = 4mm$, height of $h = 35mm$, and top opening diameter of $r = 66mm$. As shown in Fig 3 (a), a three-blade propeller is used, secured onto a bracket connected to the force sensor. The three ducts differ in the bottom curvature. The leftmost curved duct has a curved-in shape, of which the curvature is of inner radius $r = 60\ mm$. The center straight duct does not feature any curvature. The rightmost flared-out duct has the opposite feature of the curved duct, featuring a flared-out curvature of inner radius $r = 60\ mm$. All ducts were manufactured from PLA extrusion from the Creality V1 Pro 3D printer. They weigh ~34g each.

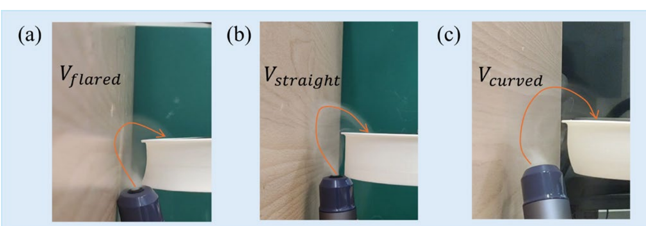

Fig. 4. Airflow visualization with handheld fog machine at PWM = 1355. (a) Airflow visualization of flared-out duct. (b) Airflow visualization of straight duct. (c) Airflow visualization of the curved duct. The visible concentration of smog can approximate the velocity of airflow.

As illustrated in Fig 4, through airflow visualization with a handheld fog machine, we can roughly observe the upward flow of air between the wall and the duct, and that the mass flow rate ($\dot{m}$) is the greatest with the curved duct installed. The rate at which smog is emitted is constant. Therefore, the whiter the smog, the slower the flow rate of the smog. The smog This is made clear by the height of the smoke flow over the lip of the duct, showing the greatest velocity of air passing through between the wall and the duct, compared to the other ducts. Inversely, $\dot{m}$ is the smallest with the flared-out duct installed. The height of the smoke flow over the lip of the duct was the least significant, displaying the lowest velocity of air. In addition, the observed upward flow of air differs from non-ducted propellers, where the airflow downwards induces a pressure difference [16].

Regarding Fig 5, as the distance between the vertical surface and the curved duct (d_{curved}) is the greatest, the mass flow rate of air ($\dot{m}_{curved}$) is the greatest. This leads to the greatest velocity of air passing between the curved duct and the vertical surface. This induced the lowest pressure compared to the other ducts, resulting in the greatest suction forces produced due to the wall-proximity effect. This matches our hypothesis that the difference in the mass flow rate of air on both sides of the propeller duct induces the wall effect.

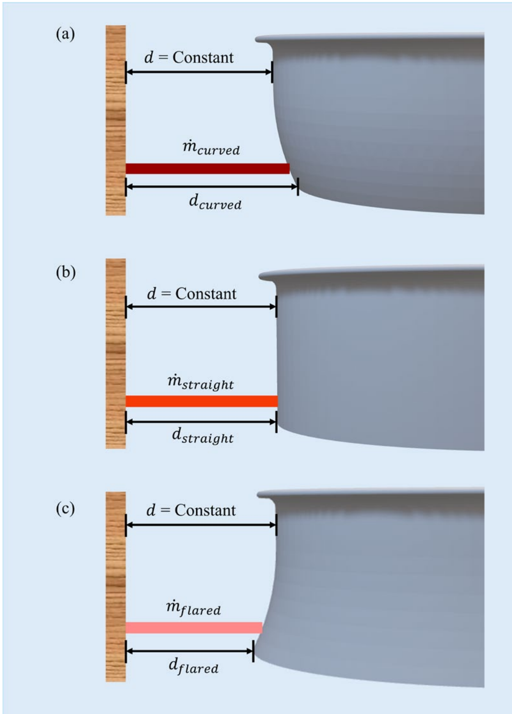

Fig 5. Illustration of ducts. Distance between ducts and the vertical surface is kept constant, while $d_{curved} > d_{straight} > d_{flared}$ due to the shape of the duct.

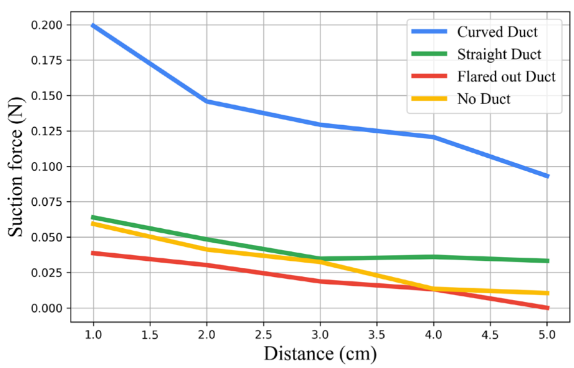

Fig 6. Suction force measurements of four different configurations of propellers. All configurations show a linear relationship between the distance from the wall and the suction force due to the wall-proximity effect.

Results from our experiment on different structures of ducts conclude that the curved duct enhances the wall-proximity effect the most. The straight duct has a similar effect on the wall-proximity effect to no duct, while the flared-out duct reduces the effect of the wall-proximity effect. This matches our hypothesis which revolves around the shape of the opening of the duct dictating v_{wall}, the velocity of air flowing between the duct and the vertical surface. These results agree with [19], in which a force of about 0.1 N pulling the quadrotor towards the wall is mentioned.

Conclusion of Experimental Results: (1) The suction force between different shapes of duct varies. The curved duct shows an enhanced wall-proximity effect compared to the flared-out duct. (2) The straight duct and the flared-out duct demonstrate a similar suction force compared with no duct. (3) The suction decreases approximately linearly with increasing distance between the wall, and the rotation speed of propellers across all modalities.

B. Investigating the effect of varying rotational speed of propeller

Experiments were also conducted at 4 different rotational speeds. Rotational speed ω can be considered as $\omega = k * PWM$, where PWM is the set rotational command. The 4 PWM values were 1155, 1255, 1355, and 1455 (k is a constant). The PWM input for hovering is roughly around 1255 to 1355 for a UAV weighing around 1000g, typical for a medium-sized quadrotor platform.

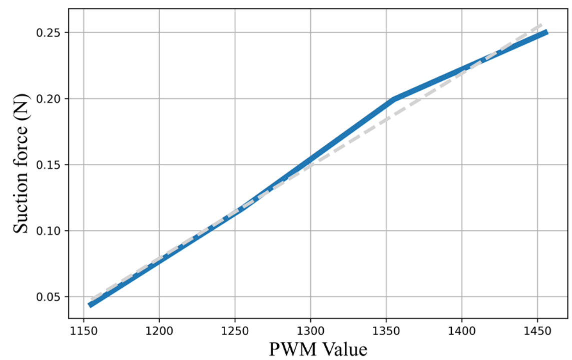

Fig 7. Suction force measurements of varying PWM values. Experimental results are represented by the blue line, with a grey trendline of equation $y = 0.000699746x - 0.760663$. The experiment was conducted at d = 1cm from the vertical surface with the curved duct installed.

Conclusion of Experimental Results: Our experimental findings indicate a linear relationship between PWN values and suction force generated by the wall-proximity effect. This result validates our model that the rotational speed of the propeller is directly proportional to the resulting suction force.

C. Effect of different designs of ducts on the thrust

Our results show negligible difference in thrust. The baseline thrust with no duct is at 3.278N. The curved duct produced 3.259N, the straight duct yielded a slight increase to 3.375N, and the flared-out duct generated the highest thrust at 3.452N.

Although previous studies have reported noticeable thrust improvements with ducted propellers [11,14], our findings reveal only minor variations across duct types. This discrepancy could be attributed to the small radius of the ducted propeller, suggesting that effect of ducts may vary significantly with propeller size. Additionally, the minor various of potential differences in the battery during testing may account for the variations in thrust produced.

IV. Discussion

The results of this paper can be implemented into control algorithms. With the suction force model completed, the distance between the vertical surface and the UAV can be determined without the use of LiDAR. Detecting the suction force and the airflow between the propeller duct and the vertical surface would be sufficient to compute the distance of the quadrotor from the wall.

Urban uses, particularly those requiring stationery hovering near a building would benefit from implementing a control algorithm taking the wall-proximity effect into account. One example is in window cleaning [20]. UAVs are required to hover near buildings with a vertical surface, and ducted UAVs would be required to protect the propellers. The wall effect therefore will have a significant impact on these larger UAV platforms, as the airflow between the ducted propellers and the vertical surface would be much more significant than smaller to medium-sized UAVs. By understanding the interaction due to the wall effect, it can be combined with the repulsion forces due to the water jet from the cleaning UAV to be integrated into a control algorithm, maintaining a constant safe distance from the vertical surface while hovering steadily.

V. Conclusion and Future work

Ducts can protect the UAV from damage after collision. Ducted propeller-based UAVs also demonstrate specific aerodynamic phenomena, for example, wall-proximity effect that impacts the control of UAVs. In addition, it is a promising way to perceive a wall. In this study, we have conducted an experimental analysis of the wall-proximity effect through tabletop experiments. Our main findings are summarized as follows:

1) Bernoulli's equation is used to explain suction forces related to the wall-proximity effect, where suction force is induced due to a difference in the velocity of air on two opposite sides of the duct, generating a difference in pressure. A d_{max} exists for all ducts, and beyond that distance the suction force is negligible.
2) The structure of the duct greatly affects the magnitude of suction forces due to the wall-proximity effect. With a curved-inward structure, the effective distance between the vertical surface and the duct is greater, increasing the suction forces. With a flared-outward structure, the effective distance between the vertical surface and the duct decreases, leading to smaller suction forces.
3) A linear relationship has been observed between the suction force and both the distance from the surface and the rotational speed.

However, the constant associated with the duct shape, which influences the magnitude of force induced from the wall-proximity effect, could not be determined. Furthermore, the influence of propeller ducts on thrust remains inconclusive, necessitating further investigation. Further studies will aim to investigate the interactive perception by leveraging the wall-proximity effect.

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