Journal of Aeronautics, Astronautics and Aviation, Vol. 56, No. 1S, pp. 373 – 380 (2024)
DOI: https://doi.org/10.6125/JoAAA.202403_56(1S).24

Aerodynamic Analysis of Cylinder to Flat Plate (CyFlap) Embedment for Agriculture Purposes

Sara Wajiha Azman, Azmin Shakrine Mohd Rafie *, Ezanee Gires

Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ABSTRACT

The goal of this research study is to conduct aerodynamic analysis for the agricultural Cylinder to Flat Plate (CyFlap) embedment that exploits the principle of Magnus effects. This study is motivated by the widespread usage of quadrotor UAVs in contemporary agriculture, which produces a downwash effect that can harm the plants. In conjunction to this, it is believed that the application of the proposed AgroCyFlaP can help to alleviate this problem. In short, the presented research work in this paper essentially covers the process of developing, manufacturing, analyzing and also wind tunnel testing of the design concept. All in all, the findings show that the proposed AgroCyFlaP demonstrates a substantial lift force around 60% more at the condition of 15º angle of attack, enabling it to transport weights that are comparable to a base UAV but without creating the downwash impact, unlike conventional rotorcraft. Although the AgroCyFlaP has shown good potential for the agricultural applications, further study is still needed to improve its aerodynamics and operation for practical implementation in the real world.

Keywords: UAV, Lift, Magnus effect, Agriculture, AgroCyFlaP, CyFlap

I. INTRODUCTION

Today, unmanned aerial vehicles (UAVs) have found applications in various fields that cover both military and civilian uses. Among others, these include their usage for parcel delivery [1], surveillance [2], aerial photography [3], reconnaissance [4] and agriculture [5]. Specifically, for the latter agriculture applications, UAVs could be operated for different tasks that include crop monitoring, crop planting, livestock management, crop spraying and ground mapping [6]. It can be taken that the use of UAVs has revolutionized the agriculture field by facilitating tasks such as aerial crop spraying, which offers great potential to improve the crop protection and agricultural fertilization [7].

Nevertheless, the efficacy of UAVs in this context has been hindered by issues such as off-target and inadequate droplet deposition during spraying operations. Moreover, since the operation of UAVs in agriculture applications is usually carried out at low flying altitudes, this exposes the plants to the powerful downwash flow field generated by the UAVs that can affect the shape of plants or damage the plants altogether [8]. Figure 1 shows a mapping of ground effects by the operation of single rotor and also quadrotor drones. As could be seen in Figure 1, the affected ground downwash area due to the rotors is rather significant.

In the meantime, the lift force that is generated from a rotating cylinder in cross-flow wind is known as Magnus force [10]. This Magnus effect, which is depicted in Figure 2, is rooted in principle of physics and it has been widely recognized in various applications including sports such as a 'curveball' in baseball. In general, the generated lift force by the Magnus effects is influenced by several factors such as the speed of rotation, the surface characteristics and also the relative motion of the surrounding air [11]. There have been also research studies that explore the use of this effect in the context of vehicle's aerodynamic, particularly in the design of the lift generation mechanism.

Manuscript received, November 11, 2023, final revision, December 5, 2023
* To whom correspondence should be addressed, E-mail: shakrine@upm.edu.my

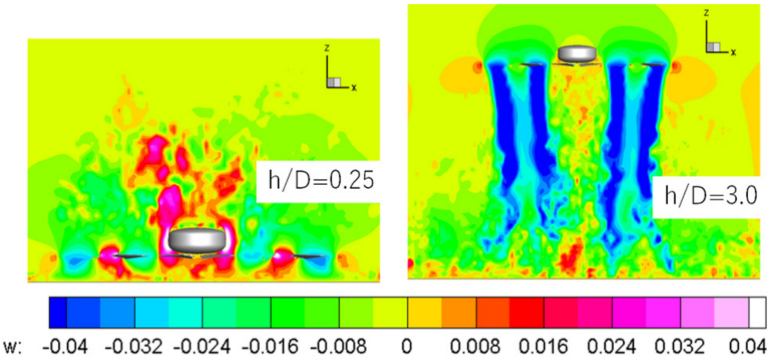

Figure 1 Mapping of ground downwash from rotor operation [9]

One of the recent developments in this particular area of applications for the Magnus effects is Cylinder to Flat Plate (CyFlaP) design, which utilizes a rotating cylinder mounted on a flat plate. This CyFlaP design has been demonstrated to possess an enhanced aerodynamic performance, including higher lift coefficient (C_L) [12]. Since this lift generating mechanism is unlike conventional fixed-wing or rotary-wing UAVs, it does not have the severe downwash flow field effects like them.

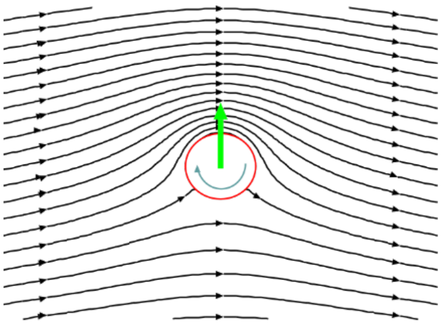

Figure 2 Illustration of Magnus effect [7]

Motivated by the need to resolve the challenges with regards to the adverse impact of downwash from operation of UAVs for agriculture applications, it is taken that using a rotating cylinder UAV in tandem with the Magnus effect holds promise for mitigating these concerns and enhancing the overall efficiency and effectiveness of the agricultural UAVs. By this notion, the CyFlap design has been adopted and tailored to suit the agriculture missions. This leads to the introduction of AgroCyFlaP design. The AgroCyFlaP offers a promising solution to address the downwash issue commonly encountered especially by quadrotor UAVs due to their rotor-based propulsion. By using Magnus effect to generate lift, this AgroCyFlaP UAV design eliminates the need for traditional rotors. This innovative approach not only circumvents the downwash problem but also presents an opportunity for more efficient and stable UAV flight for the agricultural applications.

In conjunction with this, the presented research study in this paper delves into the specific aerodynamics of the AgroCyFlaP design. To accomplish this, the experimental wind tunnel tests of the AgroCyFlaP prototype model have been conducted.

II. SETUP AND METHODOLOGY

Firstly, the design prototype model of AgroCyFlaP is fabricated, which is as depicted in Figure 3. This physical model is then used in the experimental wind tunnel testing. Wind tunnel testing is a common procedure that has been widely used to analyze aerodynamic characteristics of the tested model. For instances, wind tunnel test has been done to study aerodynamics performance of airfoils [13], wings [14] and also aircraft designs [15]. For this study, the wind tunnel tests are conducted using Open Loop Wind Tunnel (OLWT) facility at Department of Aerospace Engineering, Universiti Putra Malaysia. By performing the wind tunnel experiment, the data of forces and moments acting on the tested model under various conditions like different wind speeds or angles of attack can be gathered. Furthermore, a specialized software can also be utilized to aid in the data collection and analysis, allowing for calculation of crucial aerodynamic parameters. By using the gathered data, both Equation 1 and Equation 2 can be applied to calculate the lift coefficient, C_L and drag coefficient, C_D, respectively.

$$C_L = \frac{2L}{\rho V^2 S} \qquad (1)$$

$$C_D = \frac{2D}{\rho V^2 S} \qquad (2)$$

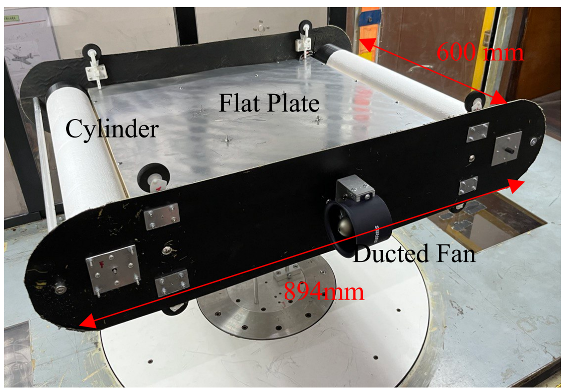

Figure 3 AgroCyFlaP design prototype model as mounted in the test section of the wind tunnel

A specialized stand has been meticulously designed and built to secure and stabilize the AgroCyFlaP model in the wind tunnel's test area as could also be seen in previous Figure 3. This stand is depicted in Figure 4 and it can offer flexibility in manipulating the model's angles, allowing for the testing of different variables and also configurations. The comprehensive set-up is designed to ensure a precise and effective aerodynamic testing of the AgroCyFlaP. The mass of the AgroCyFlaP is 5.57 kg, excluding the payload. This setup also allows the angle of the AgroCyFlaP to be manipulated for the OLWT testing.

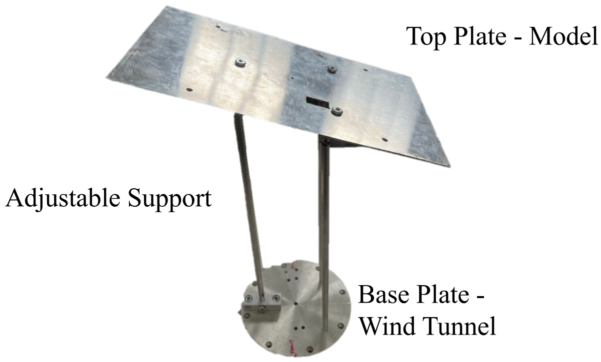

Figure 4 Special stand for the wind tunnel testing

In addition, pre-test verification assessment or calibration of the component balance system has been carried out to ensure proper accuracy and reliability of the experimental data. For this study, the conducted pre-test assessment includes measuring the value of rotations per minute (RPM) for the spinning cylinders and determining the air density in the wind tunnel environment. The RPM values for the spinning cylinders are recorded to provide a baseline reference for the wind tunnel experiments. These measurements have revealed the consistent RPM range of approximately between 3000 to 3200. This data serves as a crucial reference point for assessing the impact of design changes on the rotational speed of the cylinders. Moreover, the air density in the wind tunnel is evaluated to guarantee that the experimental conditions are closely resembling the actual meteorological conditions. The calculation is done by using Equation 3. Accurate determination of air density is of paramount importance since it directly influences the resultant aerodynamic performance and also the behavior of the AgroCyFlaP model during the wind tunnel testing.

$$\rho = \frac{P}{RT} \tag{3}$$

The wind tunnel testing for the AgroCyFlaP model is performed at four different pitch angles, which are at 0 °, 5 °, 10 ° and 15 °. The obtained experimental results are then analyzed to establish the aerodynamic characteristics for the AgroCyFlaP model. It should be noted that the results are compared with those for the JMR-X1100 Agricultural Sprayer Drone, which is selected as the reference baseline UAV in this study that represents the prominent contender within the agricultural UAV market. This particular model is singled out due to its current status as the foremost 5-kg payload UAV in the market and it boasts maximum takeoff weight of 13 kg and speed range spanning from 1 m/s to 9 m/s. The comparison helps to highlight the strengths and weaknesses of the AgroCyFlaP.

III. RESULTS AND DISCUSSION

A total of five different case settings are defined for the wind tunnel experiments in this study to evaluate the aerodynamic performance of the AgroCyFlaP, providing valuable insights into its lifting capabilities and behaviors under various conditions. The case settings are stationary spinning cylinder at four different pitch angles of 0 °, 5 °, 10 ° and 15 °, and rotating spinning cylinder at a pitch angle of 0 °. In the stationary cases, the spinning cylinder is not rotated whereas for the rotating case, the cylinder is rotated with RPM between 3000 to 3200.

Figure 5 shows the obtained experimental results for the case of rotating spinning cylinder at a pitch angle of 0°. As can be observed, a significant lift value of 76.11 N, or approximately 7.8 kg, is achieved. This indicates that the AgroCyFlaP possesses more than sufficient lift to support its own structure without the presence of a payload. Such a substantial lift capacity confirms the design's capability to meet the necessary lift specifications. On the other hand, Figure 6 presents the case results for stationary spinning cylinder at pitch angle of 0 °. It could be seen in the figure that the AgroCyFlaP still has a remarkable generated lift value of 58.51 N, or around 5.90 kg. This demonstrates that even without having its cylinders rotating, the AgroCyFlaP can still generate considerable lift.

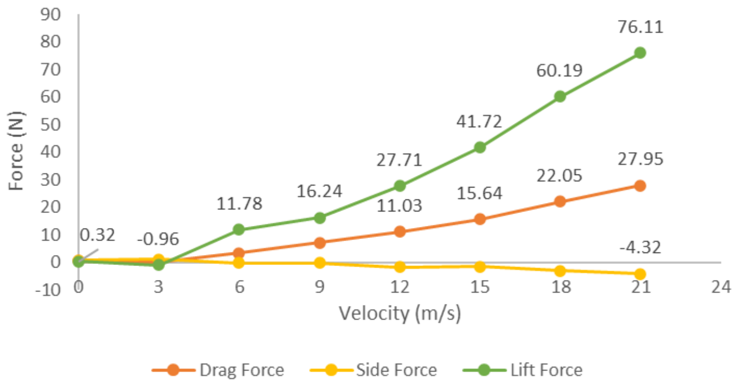

Figure 5 Experimental results for AgroCyFlaP with rotating spinning cylinders at pitch angle of 0°

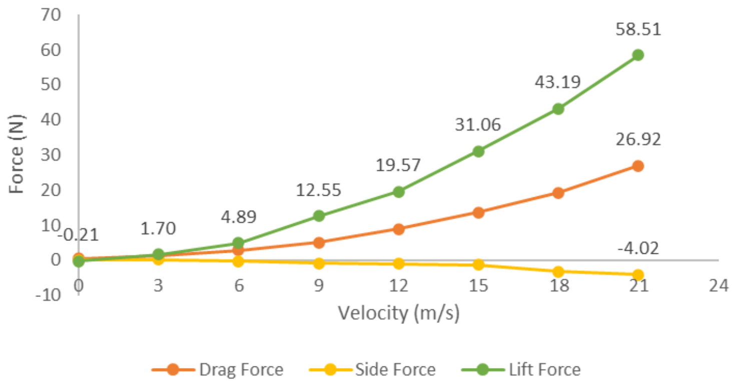

Figure 6 Experimental results for AgroCyFlaP with stationary spinning cylinders at pitch angle of 0°

Furthermore, for the stationary cases of the spinning cylinder for the AgroCyFlaP model, the pitch angle is then varied to 5 °, 10 ° and also 15 °. Figure 7 depicts the results for the case at pitch angle of 5 °, which shows that the lift generated is increased as expected with the increase in air speed, reaching 105.13 N or 10.72 kg. This indicates that the Magnus effect lift is substantial enough to support the AgroCyFlaP's structure and potential payload. Meanwhile, Figure 8 and Figure 9 present the results for the stationary spinning cylinder cases at pitch angles of 10 ° and also 15 °, respectively. In Figure 8, the generated lift value appears to further increase from that of the previous case at pitch angle of 5 °, reaching 155.13 N or approximately 15.80 kg. This finding demonstrates the direct relationship between the pitch angle and generated lift force, with higher angles producing stronger lift forces. However, it is important to note that the drag force is also increased with the increase in pitch angle, implying that there is a trade-off between these two aerodynamic forces. Lastly, from Figure 9, the generated lift value can be seen to grow even higher as the pitch angle is further increased to 15°. The recorded value of lift has increased significantly to 213.38 N or about 21.80 kg. This result further supports the correlation between the pitch angle and generated lift force for AgroCyFlaP model. At the same time, the results also highlight the associated increase in drag.

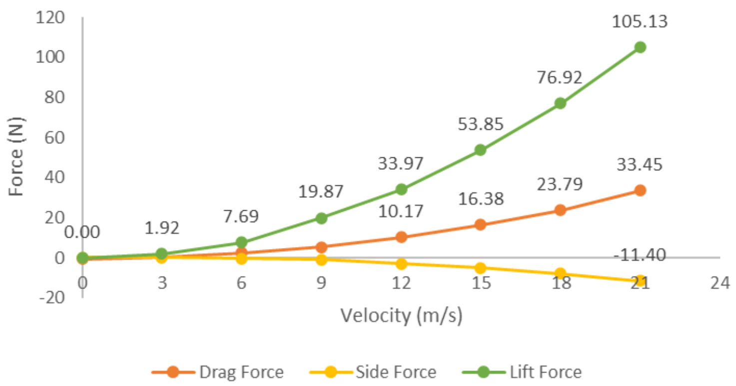

Figure 7 Experimental results for AgroCyFlaP with stationary spinning cylinders at pitch angle of 5°

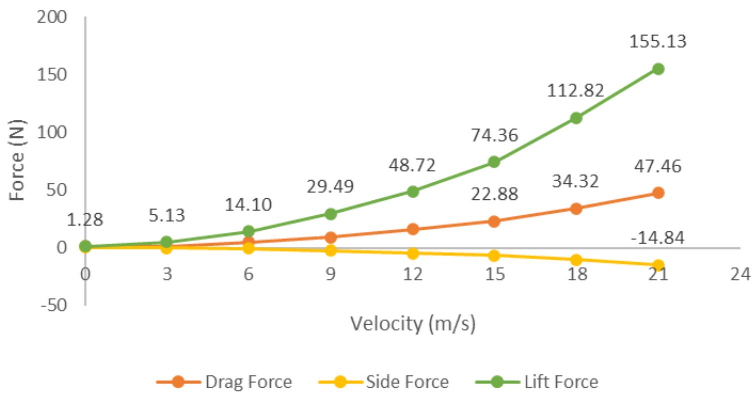

Figure 8 Experimental results for AgroCyFlaP with stationary spinning cylinders at pitch angle of 10°

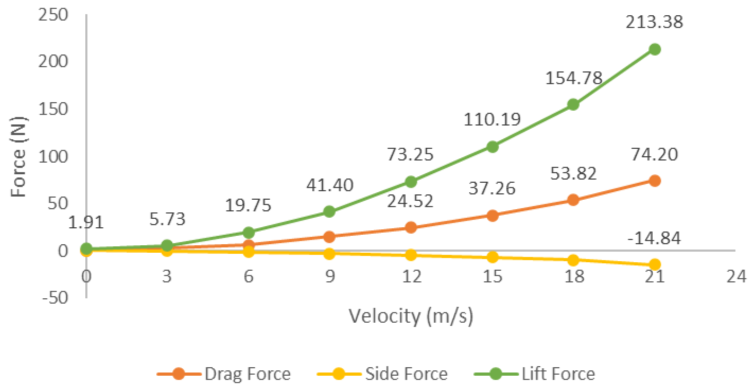

Figure 9 Experimental results for AgroCyFlaP with rotating spinning cylinders at pitch angle of 15°

Table 1 summarizes the calculated C_L value for each of the five experimental cases. Note that Case 1 here refers to the case of rotating spinning cylinder at a pitch angle of 0 °. Meanwhile, Case 2 to Case 5 correspond the cases of stationary spinning cylinder with the pitch angles of 0 °, 5 °, 10 ° and 15 °, respectively. It is observed that the highest C_L value of 2.957 is obtained in Case 5 for airspeed velocity of 3 m/s. In contrast, the minimum C_L value is observed at airspeed velocity of 3 m/s for Case 1. Significantly, the C_L values associated with the airspeed velocities of 15 m/s, 18 m/s and 21 m/s are highlighted. Results at these velocities suggest the relative stability of the C_L values in contrast to those at other velocities that seem to be greatly influenced by turbulent conditions.

In addition, a further examination of Case 1 involving the cylinder rotation provides the valuable insights into the influence of this rotational aspect on AgroCyFlaP system's lift generation. As depicted in Figure 10, conducting tests with the cylinder rotation yields a substantially higher lift force which is different by 30% compared to tests without cylinder rotation. This can be translated into additional possible payloads for the UAV. This observation unequivocally demonstrates that rotating the cylinders contributes significantly towards enhancing the AgroCyFlaP's lift force. The pronounced increase in lift, as evident in Figure 10, underscores the pivotal role of cylinder rotation as a crucial component that dictates the AgroCyFlaP's aerodynamic performance.

Table 1 Resultant lift coefficient

Velocity (m/s)	Calculated C_L Value				
	Case 1	Case 2	Case 3	Case 4	Case 5
3	-0.343	0.611	0.690	1.840	2.057
6	1.057	0.439	0.690	1.265	1.771
9	0.647	0.500	0.792	1.175	1.650
12	0.621	0.439	0.762	1.092	1.642
15	0.599	0.446	0.773	1.067	1.581
18	0.600	0.430	0.767	1.124	1.542
21	0.557	0.428	0.770	1.136	1.562

Table 2 Resultant drag coefficient

Velocity (m/s)	Calculated C_D Value				
	Case 1	Case 2	Case 3	Case 4	Case 5
3	0.001	0.460	0.186	0.456	1.028
6	0.299	0.253	0.216	0.456	0.543
9	0.286	0.204	0.213	0.372	0.597
12	0.247	0.201	0.228	0.361	0.550
15	0.224	0.195	0.235	0.328	0.535
18	0.220	0.192	0.237	0.342	0.536
21	0.205	0.197	0.245	0.347	0.543

In similar fashion, summary of results for C_D values is tabulated in Table 2. As can be observed from the results, the highest C_D value is recorded as 1.028, which is in Case 5 at the airspeed of 3 m/s. On the contrary, the lowest C_D value is found for Case 1 at the airspeed velocity of 3 m/s. This lowest C_D value is 0.001. Once again, corresponding rows for the airspeed velocities of 15 m/s, 18 m/s and 21 m/s are highlighted and they indicate that the C_D values at these airspeed velocities are the most stable. On the other hand, because of turbulence, C_D values at lower velocities continue to be unstable similar to previous C_L values.

In the meantime, Figure 11 illustrates the connection between pitching angle and generated lift force. The plots clearly show a positive relationship between the pitching angle and the lift force. As the pitching angle increases, so does the generated lift force. The results imply that altering the pitching angle will directly influence the amount of lift force generated by the AgroCyFlaP design. These findings underscore how the pitching angle significantly affects the lift force in this experimental setup. Moreover, Figure 12 is showing the plot of C_L versus pitch angle. It is good to note that the C_L value at pitch angle of 0° is 0.435. This indicates that the C_L value might be influenced by the nonrotating cylinder. If the wind tunnel testing is repeated with rotating cylinder, it is possible that the C_L value could be even higher. The graph also shows a continuous increase of C_L with the pitch angle, suggesting that higher pitching angles could still be further explored without negatively impacting the lift performance. Therefore, there is room to investigate how the higher pitching angles will affect the lift coefficient.

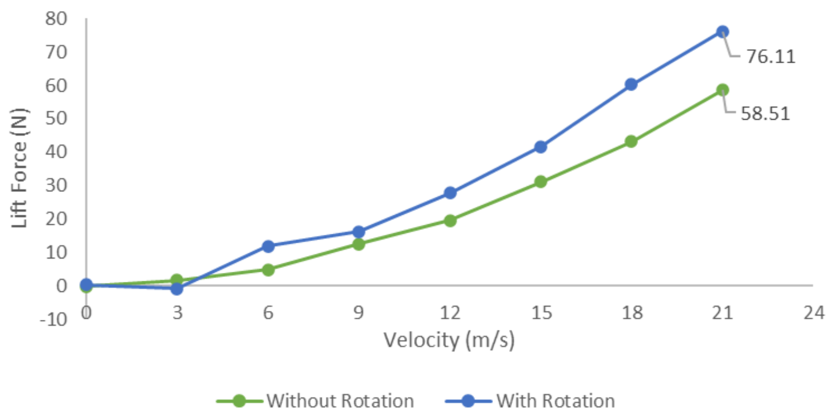

Figure 10 Plot of rotation effects on the generated lift force for AgroCyFlaP

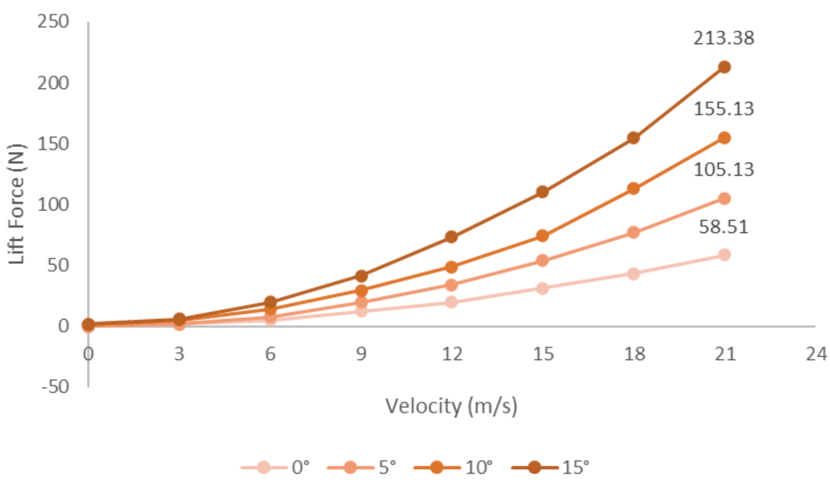

Figure 11 Plot of pitch angle effects on the generated lift force for AgroCyFlaP

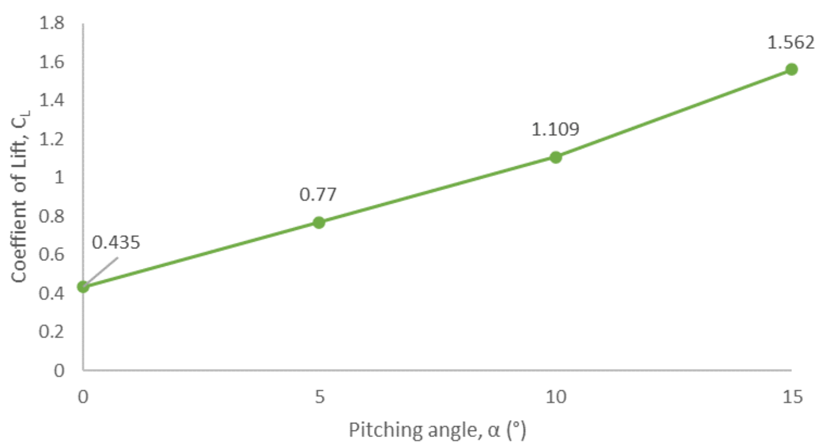

Figure 12 Plot of lift coefficient versus pitch angle for AgroCyFlaP

The plot of C_D versus pitch angle is shown in Figure 13. It is clear from the figure that C_D value is increasing as the pitch angle increases. This means that higher pitching angles result in higher air resistance and drag, potentially affecting how well the AgroCyFlaP performs in the air. On the other hand, Figure 14 presents the plot of lift-to-drag ratio versus pitch angle. The plot indicates that the highest lift-to-drag ratio occurs between 5° and 10°, which can be approximated as 8°. This is the best pitch angle where the AgroCyFlaP performs at its best.

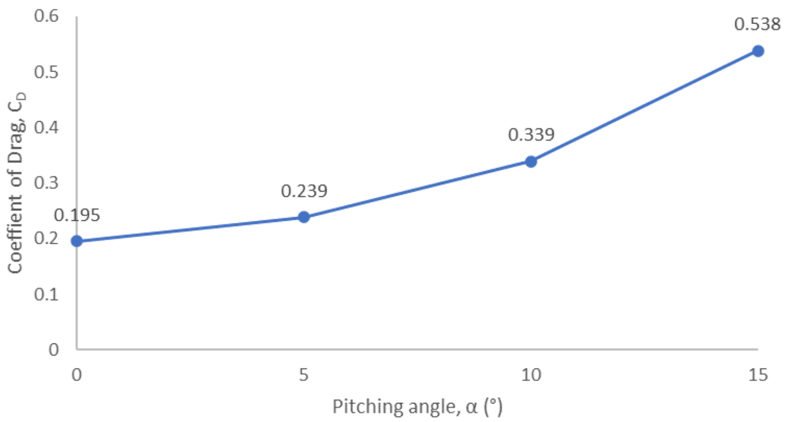

Figure 13 Plot of drag coefficient versus pitch angle for AgroCyFlaP

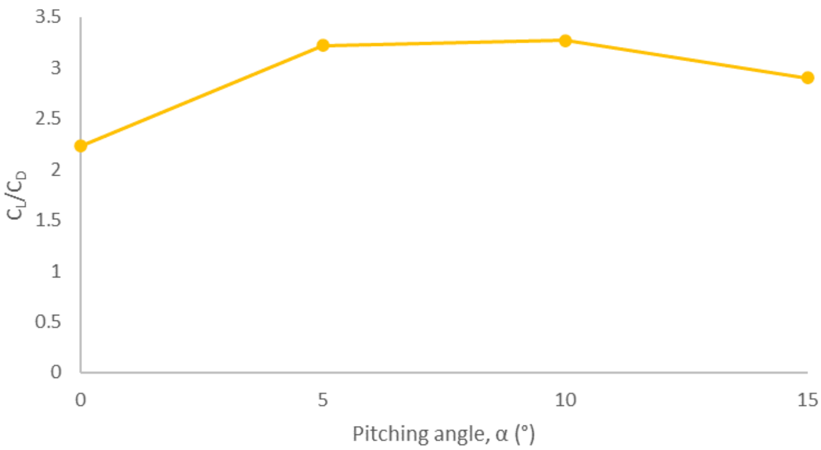

Figure 14 Plot of lift-to-drag ratio versus pitch angle for AgroCyFlaP

IV. CONCLUSION

In this study, AgroCyFlaP UAV design is developed to address the prevalent issue of downwash impact in the agricultural sector. The results of this research study have successfully demonstrated that the AgroCyFlaP, utilizing the Magnus effect, can conceptually eliminate almost 90% the downwash effects since the rotating cylinder will not produce directly wind velocity downward compare to conventional rotor blade, while still maintaining the comparable flight and payload capabilities with those of the conventional UAVs. This achievement can be taken as a significant technological advancement within the field of agricultural UAVs. Although the AgroCyFlaP has shown good potential for agricultural applications, further study is still needed to improve its aerodynamics and operation for practical implementation in the real world.

ACKNOWLEDGMENTS

The authors wish to thank Department of Aerospace Engineering, Universiti Putra Malaysia for providing the fabrication and wind tunnel facilities for this work.

REFERENCES

[1] Lin CE, Li CC, Shao PC, Luo CF, “Precision UAV parcel delivery using QR code recognition,” *Journal of Aeronautics, Astronautics and Aviation*, Vol. 51, No. 3, 2019, pp. 275-289.

[2] Perez D, Maza I, Caballero F, Scarlatti D, Casado E, Ollero A, “A ground control station for a multi-UAV surveillance system: design and validation in field experiments,” *Journal of Intelligent & Robotic Systems*, Vol. 69, 2013, pp. 119-130.

[3] Gurtner A, Greer DG, Glassock R, Mejias L, Walker RA, Boles WW, "Investigation of fish-eye lenses for small-UAV aerial photography," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 47, No. 3, 2009, pp. 709-721.
[4] Iscold P, Pereira GA, Torres LA, "Development of a hand-launched small UAV for ground reconnaissance," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 46, No. 1, 2010, pp. 335-348.
[5] Yousefi DM, Rafie ASM, Al-Haddad SAR, Azrad S, "A systematic literature review on the use of deep learning in precision livestock detection and localization using unmanned aerial vehicles," *IEEE Access*, Vol. 10, 2022, pp. 80071-80091.
[6] Marzuki OF, Teo EYL, Rafie ASM, "The mechanism of drone seeding technology: a review," *The Malaysian Forester*, Vol. 84, No. 2, 2021, pp. 349-358.
[7] Lan Y, Shengde C, Fritz BK, "Current status and future trends of precision agricultural aviation technologies," *International Journal of Agricultural and Biological Engineering*, Vol. 10, No. 3, 2017, pp. 1-17.
[8] Shi Q, Liu D, Mao H, Shen B, Li M, "Wind-induced response of rice under the action of the downwash flow field of a multi-rotor UAV," *Biosystems Engineering*, Vol. 203, 2021, pp. 60-69.
[9] Tanabe Y, Sugawara H, Sunada S, Yonezawa K, Tokutake H, "Quadrotor drone hovering in ground effect," *Journal of Robotics and Mechatronics*, Vol. 33, No. 2, 2021, pp. 339-347.
[10] Marzuki OF, Rafie ASM, Romli FI, Ahmad KA, "Torque performance study of Magnus wind turbine," *International Review of Mechanical Engineering*, Vol. 9, No. 1, 2015, pp. 38-42.
[11] Marzuki OF, Rafie ASM, Romli FI, Ahmad KA, Hamid MFA, "An overview of horizontal-axis Magnus wind turbines," *IOP Conference Series: Materials Science and Engineering*, Vol. 405, No. 1, 2018, 012011.
[12] Ali HM, Rafie ASM, Ali SAM, Gires E, "Computational analysis of the rotating cylinder embedment onto flat plate," *CFD Letters*, Vol. 13, No. 12, 2021, pp. 133-149.
[13] Kamal NNM, Basri AA, Basri EI, Sultan MTBHH, Rafie ASM, Hamid MFA, "Validation and verification of aerodynamics loading of Schrenk approximation, Prandtl lifting-line and computational fluid dynamics with experiment on NACA series," *Journal of Aeronautics, Astronautics and Aviation*, Vol. 53, No. 2, 2021, pp. 283-288.
[14] Yang LJ, Kapri N, Waikhom R, Unnam NK, "Fabrication, aerodynamic measurement and performance evaluation of corrugated flapping wings," *Journal of Aeronautics, Astronautics and Aviation*, Vol. 53, No. 1, 2021, pp. 83-94.
[15] Ocokoljić G, Rašuo B, Kozić M, "Supporting system interference on aerodynamic characteristics of an aircraft model in a low-speed wind tunnel," *Aerospace Science and Technology*, Vol. 64, 2017, pp. 133-146.