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Design Analysis of Open and Ducted Propellers in UAV Application

(Analisis Reka Bentuk Kipas Terbuka dan Saluran dalam Aplikasi UAV)

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ABSTRACT

The aim of the study was to determine the feasibility of implementing a ducted propeller system for small scale drones. 5" propeller drones are common in first person view (FPV) drone racing and cinematography, increasing the likelihood of injury due to untrained pilots, of which the majority are laceration injuries due to the propeller blades. Furthermore, the addition of a duct improves the thrust output of the entire system. A few key parameters are identified, of which were manipulated to determine the optimum values through a series of ANSYS Fluent CFD simulations. Introducing a duct is shown to reduce the lift a propeller produces; however, the reduction is offset by the lift generated by the duct. Blade tip clearance was investigated, with the optimum value found to be 0.25 mm, producing the most lift from the duct and least reduction of propeller lift, and with thrust outputs up to 35.568% more in some cases compared to open propeller. It was observed that increasing the BTC significantly reduced duct lift. Diffuser length simulations provided unconclusive results, with the duct lift varying depending on the diffuser length. However, the optimum diffuser length was determined to be 65 mm with respect to thrust outputs. In comparison, inlet lip radius shows a clear pattern, deviating from the optimum value of 16.5 mm reduces the duct lift produced, with smaller values severely decreasing performance.

Keywords: Propeller drone; ANSYS Fluent; parametric; Drone blade design

ABSTRAK

Tujuan kajian ini adalah untuk menentukan kebolehlaksanaan pelaksanaan sistem kipas saluran untuk dron berskala kecil. Drone kipas 5" adalah perkara biasa dalam pandangan orang pertama (FPV) perlumbaan drone dan sinematografi, meningkatkan kemungkinan kecederaan akibat juruterbang yang tidak terlatih, di mana majoritinya adalah kecederaan luka akibat bilah kipas. Tambahan pula, penambahan saluran meningkatkan output tujahan keseluruhan sistem. Beberapa parameter utama dikenalpasti, yang telah dimanipulasi untuk menentukan nilai optimum melalui satu siri simulasi CFD AnSYS Fluent. Memperkenalkan saluran ditunjukkan untuk mengurangkan lif yang dihasilkan oleh kipas; Walau bagaimanapun, pengurangan diimbangi oleh lif yang dihasilkan oleh saluran. Pelepasan hujung bilah disiasat, dengan nilai optimum didapati 0.25 mm, menghasilkan lif paling banyak dari saluran dan pengurangan paling sedikit lif kipas, dan dengan output tujahan sehingga 35.568% lebih banyak dalam beberapa kes berbanding dengan kipas terbuka. Telah diperhatikan bahawa meningkatkan BTC mengurangkan kenaikan saluran dengan ketara. Simulasi panjang diffuser memberikan hasil yang tidak konklusif, dengan angkat saluran berbeza-beza bergantung pada panjang penyebar. Walau bagaimanapun, panjang penyebar optimum ditentukan sebagai 65 mm berkenaan dengan output tujahan. Sebagai perbandingan, jejari bibir masuk menunjukkan corak yang jelas, menyimpang dari nilai optimum 16.5 mm mengurangkan angkat saluran yang dihasilkan, dengan nilai yang lebih kecil mengurangkan prestasi dengan ketara.

Kata kunci: Kipas Saluran Dron; ANSYS Fluent; Parametrik; Rekabentuk Bilah Dron

INTRODUCTION

With the progression of technology steadily accelerating, the applications of unmanned aerial vehicles (UAV) are expanding. UAVs were designed at its conception with military applications in mind, typically for ISR missions (intelligence, surveillance, and reconnaissance). UAV applications differ with their sizes; larger class UAVs such as the General Atomics MQ-1 Predator provide aerial reconnaissance and saw use in offensive operations by the USAF due to its missiles and other munitions, whereas smaller UAVs such as the Honeywell RQ-16A T-Hawk are used in smaller scale reconnaissance by the US Army (Agbeyangi et al. 2016).

Over the years, UAV technology has broadened in potential, being utilized in fields of agriculture with regards to application such as crop monitoring, soil and field scrutiny, crop spraying, and crop health assessment, environmental and forest monitoring, as well as law enforcement applications such as security surveillance and search and rescue (Tripicchio et al. 2015; Yusoff et al. 2022). The UAV configurations are typically based on the task at hand, with the configurations including rotary vertical takeoff and landing (VTOL), fixed wing and hybrid VTOLs.

Fixed wing UAVs have several advantages over rotary UAVs, mainly their endurance and speed. Fixed wing UAVs operate on a similar principal to airplanes in that an airfoil is utilized to produce lift and only thrust is required to move the drones, making them very power efficient in comparison to rotary UAVs as rotary systems require more power for control stabilization, flight, and hovering. VTOL systems dominate in situations where more operational control is required. For example, a fixed wing UAV would typically need a runway or some clearance to gain speed and lift, whereas a VTOL UAV can simply deploy in area of tight clearances (given a minimum space is met). Another main advantage of VTOL UAVs is the hovering capability, which is useful in situations where the UAV needs to remain stationary in the air for an objective, e.g., security surveillance.

RESEARCH MOTIVATION

The usage of small unmanned aerial vehicles in the present and will soon be a major part of future integration of technology in various fields, such as agriculture, surveillance and security, wildlife management, package delivery, etc. With this, it is important to note what impact the UAVs have on the environment. One such impact is the level of acoustic noise generated by the UAVs during certain missions where stealth is important and detection would result in failure of the mission, such as during nighttime surveillance or wildlife tracking side from that, it also contributes to noise pollution, which comes with numerous adverse health effects (Jariwala 2017). Aerodynamic noise in this case is usually the result of vortices located on the wings, rotors and/or propellers, increasing with wing or blade span loading and speed.

Another impact is the increased likelihood of injuries during collisions (ASSURE 2017). The Alliance for System Safety of UAS through Research Excellence (ASSURE) has identified 3 dominant injury types: blunt force trauma, lacerations, and penetration injuries. Laceration injuries are mainly the cause of unguarded blade guards; and while having limited potential for fatality, has already publicly documented disability injuries, such as inflicting permanent blindness.

The main aim of the project was to develop a safer alternative that will reduce drone related injuries (specifically lacerations) while producing the same thrust at the same power output. Research has been conducted on ducted fan VTOLs; in effect, propellers are ducted, which protects the user against the blades while providing a surface that prevents blade tip vortexes to form, hence improving lift. This project contains the specific objectives as follows:

1. Determine the parameters that influence thrust output of duct implementations via literature review
2. Perform CFD investigation of duct implementation with respect to consumer grade drones (i.e., smaller 5” propeller drones)
3. Determine how altering the parameters (blade tip clearance, inlet lip radius, diffuser length) affects the thrust generated (both by propeller and duct).

EXPERIMENTAL SETUP

Figure 1 presented the two main phases was conducted in this study, Phase 1: Determine the design parameters using literature survey approach and Phase II is design analysis and evaluation

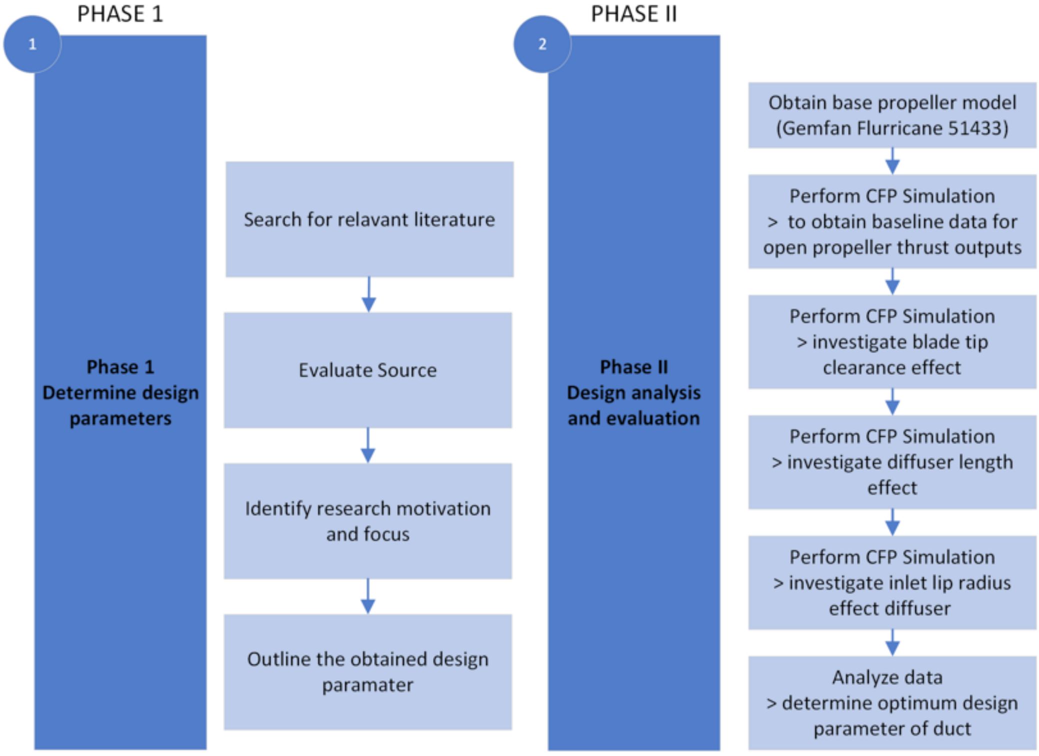


FIGURE 1. Overview of Research Methodology

Phase 1: Determination of design parameters influencing ducted propeller thrust output

In the Phase 1, a literature survey was conducted to determine the design parameter that influence the ducted propeller. It is providing an overview of the existing knowledge, and to ensure the relevant study that supports the existing experiment. This phase begins with searching the relevant studies, in several scholar database (i.e., Scopus, WoS, JSTOR, IEEE Xplore). This stage started with listing the keyword related to our study, which is include key concepts of design parameters in ducted propeller thrust output. Next, the relevant articles were evaluated and selected to determine the design parameters. Once the relevant articles were determined, the design parameter were identified. Based on the literature survey (Priatmoko, & Nirbito, 2019; Zhang, Ji, Zhou & Zhang, 2020; Li, Yonezawa, & Liu, 2021). Three main design parameters as shown in Figure 2 were obtained and used in this study such as Blade-tip clearance, δ_t , Lip radius, Rl_{ip} and Diffuser length, L_d

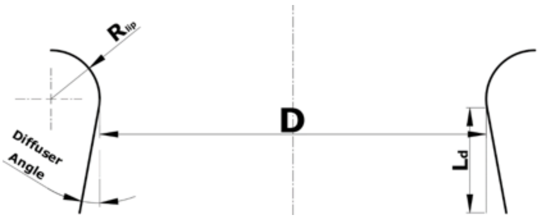


FIGURE 2. Design Parameters Observed

Phase 2: Design and analyze duct and propeller performance

In the Phase 2, this study was aimed to determine the effects on thrust output by varying key parameters of the selected design. In this phase, CFD simulation is utilized through ANSYS Fluent as shown in Figure 1. For this study, a base propeller size of 5” is chosen due to its common applications in FPV drone racing and cinematography (and hence, the likelihood of injury is higher due to more untrained pilots, ASSURE 2017). The propeller is typically paired with a 2400KV motor and connected to a 3S battery (11.1V output), hence a max RPM of 26640 rpm is derived. The propellers are subjected to various RPM from 0 to 26400rpm at hover conditions (i.e., freestream/ inlet velocity of 0m/s) to study the lift generated by both propeller and duct.

CFD GEOMETRY SETUP

CFD geometry setup was conducted in order to observe changes in thrust output with the implementation of propeller ducts. A base propeller is required, and this study have obtained 3D model of the Gemfan 51466 in GrabCAD as illustrated in Figure 3. Based on the study conducted by Kutty, & Rajendran (2017), the simulation of Small APC propellers, a multi-reference frame is utilized, with a rotating domain and a static domain present. The static domain is consistent (600mm×600mm×800mm) and the upstream / downstream boundary conditions must be set at a sufficient distance (ANSYS Fluent Guide). The rotating domain is set at 1.2Dt diameter and 0.2Dt height encompassing the open propeller, whereas the diameter is set to conform to the duct walls in ducted simulations. Besides, in order to simulate static / hover conditions, a two pressure-outlets setup were chosen. The alternative of having 0 m/s velocity inlet and a pressure outlet yields similar results, but a 3D streamline can be shown through the two pressure-outlet setups. Named selections for the propeller and ducts were created.

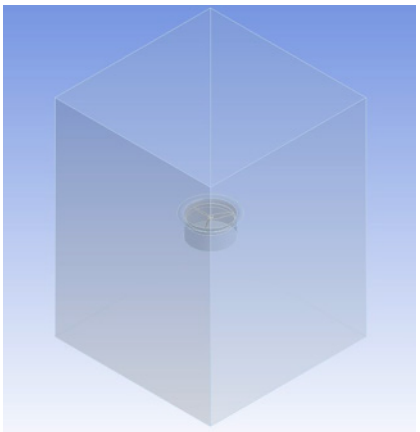
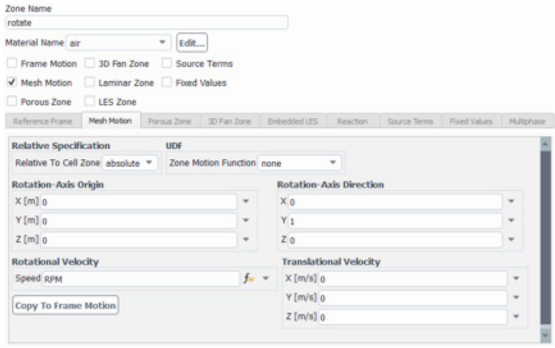


FIGURE 3. Geometry Setup

ANSYS MESH AND FLUENT SETUP

Due to the limited timeframe, mesh independence study was not feasible as it would need to be conducted across multiple designs. Standard unstructured mesh was also chosen, as it is deemed suitable by Kutty, & Rajendran (2017) although modifications in size were made to ensure skewness is kept below 0.8. Furthermore, ANSYS Student License limits number of elements to 512K. Transient is chosen as sliding mesh motion requires transient to work properly (ANSYS Fluent 2020 Guide). The mesh is set to rotate, and the RPM is set as an input parameter. A study conducted by Sadikin et. al (2018) served to determine the best turbulence model for airfoil (between Realizable k-ε, k-ω SST and Spalart-Allmaras), concluding that Realizable k-ε is optimum due to the delay of flow separation occurrences. Hence, Realizable k-ε is chosen with scalable wall function for near wall treatment as presented in Figure 4. Report files are then created for lift forces acting on the duct, propeller as well as the combination of the two, and set as output parameters. As transient is used, 50 timesteps with a timestep size of 0.003s along with 100 iterations / timestep is chosen, although 50 iterations/timestep was able to produce results that converge within 30 timesteps. The solution is set to be exported for CFD-Post at the end of each simulation



Zone Name
rotate
Material Name air
☐ Frame Motion ☐ 3D Fan Zone ☐ Source Terms
☑ Mesh Motion ☐ Laminar Zone ☐ Fixed Values
☐ Porous Zone ☐ LES Zone

Relative Specification
Relative To Cell Zone absolute
UDF
Zone Motion Function none
Rotation-Axis Origin
X [m] 0
Y [m] 0
Z [m] 0
Rotation-Axis Direction
X 0
Y 1
Z 0
Rotational Velocity
Speed RPM
Translational Velocity
X [m/s] 0
Y [m/s] 0
Z [m/s] 0

FIGURE 4. Cell Zone Conditions for Rotating Domain

There are three experimental setup was designed with different RPM setup ranging from 2400rpm – 26400rpm for both lift and duct propeller.

1. Simulation of Open Propeller
2. Effects of Blade Tip Clearance; 0.125 mm, 0.25mm, 0.5mm, 1.0 mm, 2.5mm
3. Effects of Diffuser Length; 35mm, 45mm, 55mm, 65mm
4. Effects of Inlet Lip Radius;12 mm, 15mm, 16.5mm, 18mm.

RESULTS AND DISCUSSIONS

This section presented effects of changing parameters has on thrust output on both the duct, the propeller, and the combination of both.

EFFECTS OF BLADE TIPS CLEARANCE

This set of simulations were run with a consistent 65 mm diffuser length (50%Dt) and 16.5mm inlet lip radius (13%Dt) for 0.125 mm, 0.25mm, 0.5mm, 1.0 mm, 2.5mm design parameters.

FIGURE 5. BTC, Comparison of Combined Lift (N) vs RPM

Based on Figure 5, the optimum BTC is determined to be 0.25 mm. Compared to the thrust outputs of the open propeller, the 0.25 mm BTC provided output changes ranging between 21.3% up to 35.6% increase in thrust. In all cases, the highest thrust output change was seen at 16800 rpm, with 0.25 mm BTC achieving 35.6% more thrust (6.086 N vs 5.137 N) compared to open propeller setup. The max. thrust increment can also be seen at 26400 rpm, with 0.25 mm producing 3.184 N more than the base propeller. Increasing the BTC was observed to decrease overall lift (due to reductions in duct lift). Reducing the BTC below 0.25 mm has shown in Figure 6 to reduce thrust output relative to 0.25 mm.

Besides, a consistent occurrence can be seen, i.e., propeller lift reduction. Adding a duct configuration reduces the lift produced by the propeller, which is reduced due to pressure reduction and subsequently, an increase in inflow velocity.

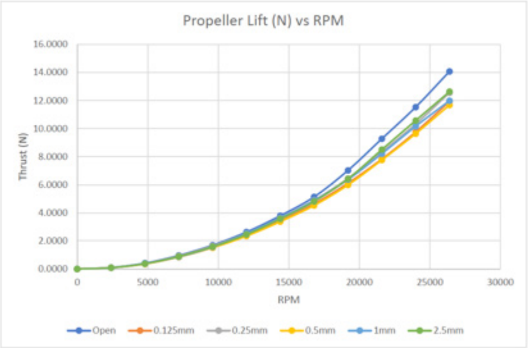


FIGURE 6. BTC, Propeller Lift (N) vs RPM

With respect to propeller lift loss, no discernable pattern or trend can be determined as shown in Figure 7. The least propeller lift loss can be seen in 0.25mm BTC and 2.5mm BTC, ranging between 0.082–1.5150 N and 0.0126–1.4420 N, respectively. In comparison, the worst propeller lift loss can be seen in 0.5 mm BTC, ranging between 0.0141–2.3986 N lift loss. Hence, no conclusive remark can be made in the case of propeller lift loss due to clearance

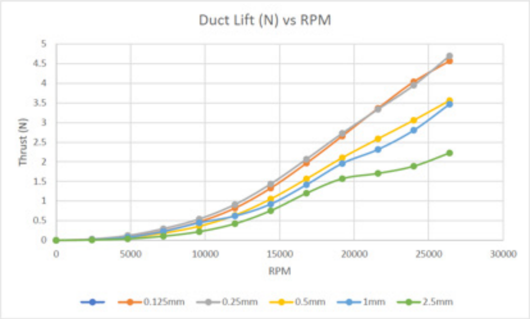


FIGURE 7. BTC, Duct Lift (N) vs RPM

The effects of varying BTC can be seen clearer with respect to duct lift. With the exception of 0.125 mm BTC, increasing the BTC from the optimum value of 0.25 mm significantly reduces the lift generated, showing a clear regression trend as BTC is increased. 0.25 mm BTC produced the most duct lift ranging from 0.003–4.6986 N, in comparison, 2.5 mm BTC produced the least duct lift ranging from 0.0066–2.2233 N. Hence, a conclusive statement can be made that increasing the BTC above the optimum value results in decrease in duct lift, and by extension, overall lift generated.

EFFECTS OF DIFFUSER LENGTH

As 0.25 mm BTC determined to be the optimum BTC value, Figure 8 presented the set of experiments serve to determine the optimum diffuser length, with the inlet lip radius of 16.5 mm as a constant parameter for 35mm, 45mm, 55mm, 65mm experimental design setup. The optimum diffuser length with respect to thrust remains as 65mm. Similar to previous results, the data obtained is not conclusive enough to determine any correlation or patterns. For instance, the max thrust output increase for 55 mm is 31.2%, this is then decreased to 22.96% for 45mm, and increased yet again to 30.108% for 35 mm. Overall, the least lift was produced by 45mm diffuser length

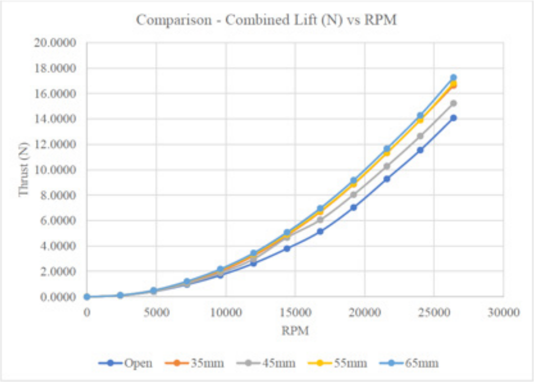


FIGURE 8. Diffuser Length, Combined Lift (N) vs RPM

Based on the Figure 9, data obtained consistently placed the 45 mm diffuser length as the lowest thrust outputs as opposed to other diffuser lengths, yet as discussed previously in BTC effects on propeller lift, a clear pattern or trend cannot be discerned from the data produced.

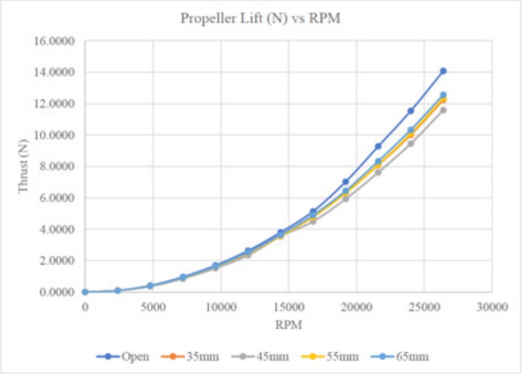
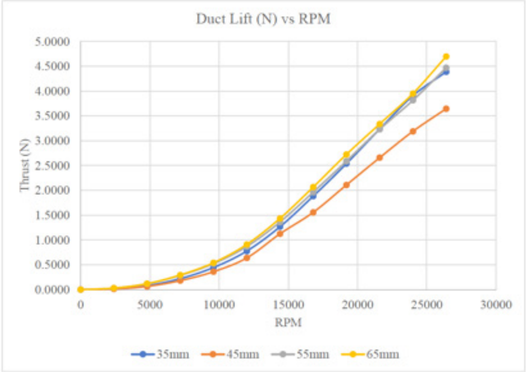


FIGURE 9. Diffuser Length, Propeller Lift (N) vs RPM

With respect to duct lift, as presented in Figure 10 similarly, there are no discernable differences between the different diffuser lengths, with the 45 mm diffuser length being an obvious outlier. A possible explanation of lower thrust may be attributed to flow separation in the inner surface of the duct, however the same effects were not seen in the 35 mm.



FIURE 10 Diffuser Length; Duct Lift (N) vs RPM

EFFECTS OF INLET LIP RADIUS

The optimum BTC of 0.25 mm along with diffuser length of 65 mm is chosen to investigate the effects of inlet lip radius. The data obtained shown in Figure 11 illustrated the optimum value of the inlet lip radius is 16.5 mm, able to output thrust up to 17.26 N, due to the highest duct lift output along with the least propeller lift reduction. With respect to overall lift, the lowest output is produced by 12 mm. A trend can be seen with decreasing the inlet lip radius; i.e., a significant decrease in performance can be observed, with 12 mm inlet lip radius providing only as much as 13.44% output and a maximum of 14.58 N (3.578% more than max thrust of open propeller). The only outlier than be seen is increasing the inlet lip radius to 18 mm, in which the performance is slightly degraded (ranging from 1.272% to 20.616% maximum increase).

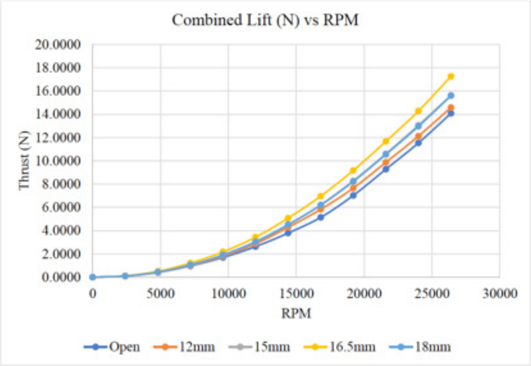


FIGURE 11. Inlet Lip Radius; Combined Lift vs RPM

Referring to the Figure 12, by comparing propeller lift data, it is observed that 15 mm and 16.5 mm inlet lip radius produce more thrust output, whereas 12 mm and 18 mm has slightly lower values, however more data for different inlet lip radius is required to form a concrete conclusion

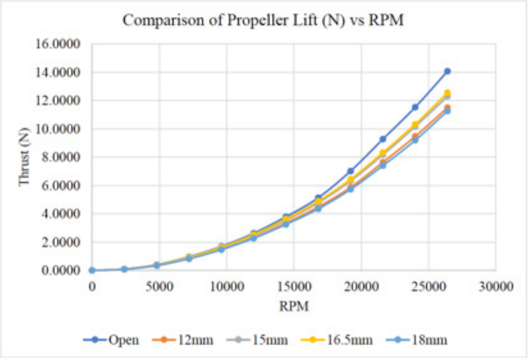


FIGURE 12. Inlet Lip Radius, Comparison of Propeller Lift (N) vs RPM

The results are more conclusive with respect to duct lift, with the outlier of 18 mm, reducing the inlet lip radius resulted in a decrease in thrust output by the duct as shown in Figure 13. However, increasing the inlet lip radius to 18 mm also resulted in a reduction of thrust output, hence it can be surmised that deviating from the optimum value results in lower thrust.

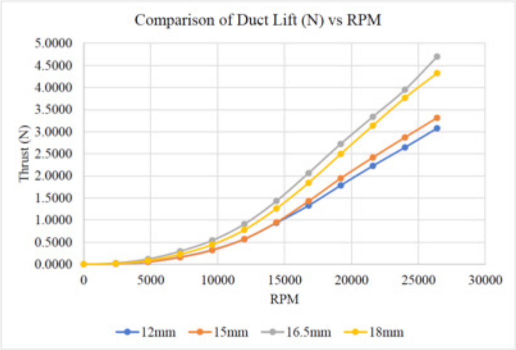


FIGURE 13. Inlet Lip Radius; Duct Lift (N) vs RPM

CONCLUSION

A base set of simulation data was obtained by varying RPM of the propeller, which allowed to know the thrust values for each RPM. From there, blade tip clearance was altered, and the best option was chosen to carry over to diffuser length, and the same was done and carried over to inlet lip radius. A breakdown of lift components into propeller and duct was crucial to understanding the effects of altering the parameters. With this, the 2nd objective of performing CFD investigation was completed. Finally, the results from the experiments were analyzed and a few key findings were highlighted, namely:

1. Performance of both duct and propeller thrust was largely determined by the blade tip clearance, with 0.25 mm BTC as the optimum value for 5” drone propellers and increasing from this value resulted in significant reductions in performance.
2. Diffuser length impacts are largely independent results-wise and show no correlation, however more data will be needed to form a conclusive statement.
3. Inlet lip radius plays a large part in overall performance; deviation from the optimum result of 16.5 mm results in significant reductions in performance by reducing the duct lift produced.
4. The propeller lift is reduced with the implementation of a duct; however, the reduction is compensated by the duct, hence a well-optimized duct is crucial to provide better performance.
5. Earlier it was mentioned by Pereira (2008) that overall performance is dependent on other parameters, and it is difficult to pinpoint the most prominent effect on thrust based on parameter adjustments. This was true in the context of the study, though based on the conclusions, the most consistent impact was through changing blade tip clearances.

This study is ongoing project with additional design analysis that will conducted, for example, have a finer value deviation from the optimum values to verify if they are the most optimum. Furthermore, more accurate results may be obtained through mesh dependence studies as well as from ANSYS licenses with element limits larger than 512K. In addition, the effects of thrust during climbing conditions (i.e., dynamic flight situations) also poses an interesting study, especially with respect to propeller lift reduction and the drag experience by the duct in dynamic conditions. Fig. 14 and Fig 15. presented the simulation of the velocity contour and streamline of the ducted propeller. We shall report for our sub-sequent publication.

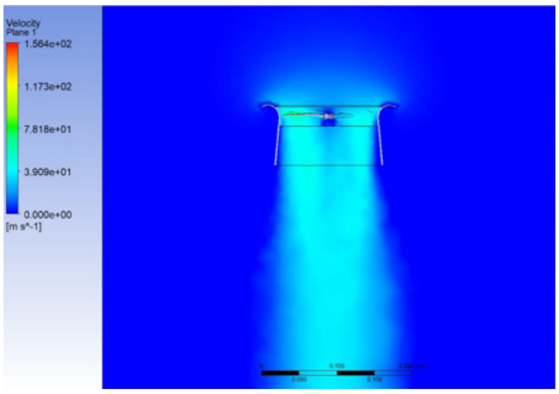


FIGURE 14. Velocity Contour of a Ducted Propeller Simulation

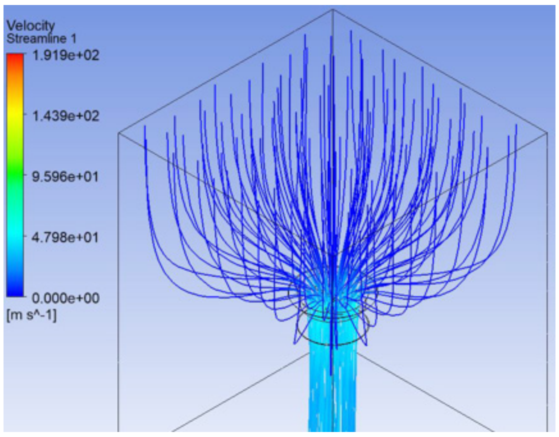


FIGURE 15. Velocity Streamline of a Ducted Propeller Simulation

REFERENCES

Agbeyangi, A. O., Odiete, J. O. & Olorunlomerue, A. B. 2016. Review on UAVs used for aerial surveillance. *Journal of Multidisciplinary Engineering Science and Technology* 3(10): 5713-5719.

Jariwala, H. J., Syed, H. S., Pandya, M. J. & Gajera, Y. M. 2017. Noise pollution & human health: A review.

Kutty, H. A. & Rajendran, P. 2017. 3D CFD simulation and experimental validation of small APC slow flyer propeller blade. *Aerospace* 4(1): 10.

Priatmoko, M. R. & Nirbito, W. 2019. Design Analysis of ducted propeller for bicopter drone propulsion. *IOP Conference Series: Materials Science and Engineering* 685(1): 012008.

Pereira, J. L. 2008. *Hover and Wind-Tunnel Testing of Shrouded Rotors for Improved Micro Air Vehicle Design*. University of Maryland, College Park.

Sadikin, A., Yunus, N. A. M., Abd Hamid, S. A., Salleh, S. M., Rahman, M. N. A., Mahzan, S. & Ayop, S. S. 2018. A comparative study of turbulence models on aerodynamics characteristics of a NACA0012 airfoil. *International Journal of Integrated Engineering* 10(1).

Tripicchio, P., Satler, M., Dabisias, G., Ruffaldi, E. & Avizzano, C. A. 2015. Towards smart farming and sustainable agriculture with drones. In 2015 International Conference on Intelligent Environments IEEE 140-143.

Yusop, F., Mustafa, S. S., Awang, M., Hassan, N. N. M. & Noor, H. M. 2022. Comparison of Pressure Distribution of Naca 0012 Between CFD Code and Experimental. *CFD Letters* 14(2): 35-41.

Zhang, C., Ji, L., Zhou, L. & Zhang, Z. 2020. Effects of different blended blade tip and winglets on aerodynamic and aeroacoustic performances of diagonal fans. *Aerospace Science and Technology* 106: 106200.