Drag Assessment of Vertical Lift Propeller in Forward Flight for Electric Fixed-Wing VTOL Unmanned Aerial Vehicle

Z. Sahwee\textsuperscript{a}, N. L. Mohd Kamal\textsuperscript{a}, S. Abdul Hamid\textsuperscript{a}, and N. Norhashim\textsuperscript{a}, N. Lott\textsuperscript{a}, M. H. Mohd Asri\textsuperscript{a}

\textsuperscript{a}Universiti Kuala Lumpur, Malaysian Institute of Aviation Technology, 43800, Dengkil, Selangor, Malaysia

Abstract. A fixed-wing UAV that is capable of vertical takeoff/landing is a hybrid aerial vehicle that could take off as helicopter and then transition into conventional airplane for forward flight. There are several powertrain configurations for the VTOL aircraft, one of them is called Separate Lift Thrust (SLT) configuration where the forward flight uses different powertrain compared to the hover phase. Without complex mechanism to store the inactive hover powertrain, the hover powertrain components added a significant amount of aerodynamic drag during forward flight. This paper presents the assessment of the drag caused by the inactive propellers during the forward cruising flight phase. For this research, 26 propeller samples with diameter from 5 inch to 9 inch were used with various configuration and materials. They were then tested in wind tunnel facility and the resultant drag was measured. The results from the wind tunnel test shows that for lowest drag penalty, smaller propeller diameter with low pitch blade provide the lowest drag. Interestingly, from the results, it shows that there is a flight speed that can provide an optimum drag from the chosen propeller. A selection of optimum motor and battery can be made in the future based on result presented in this paper to further improve the performance of the UAV.

1. Introduction

Typically, it is desired that airplanes can take off and land at fairly low speeds, so that they can use smaller and shorter airfields. The initial climb and the final descent are the most dangerous segments of a flight where most accidents occurs [1]. Various control schemes were studied to improve the reliability of flight [2]. One of the methods is by having Vertical take-off and landing capability which greatly reduces this risk because the plane is accelerated and decelerated while it is high in the air by adding margin for error and recovery. The VTOL configuration also bridges the performance gap between traditional helicopter and conventional aircraft [3]. Based on recent and projected advancements in battery specific energy, these electric VTOL (eVTOL) aircraft are anticipated to become feasible in the near term for short flights of 20-50 miles [4].

In Vertical Take-Off and Landing (VTOL) aircraft, the vertical lifting propulsion system used by Separate Lift Thrust (SLT) configuration contributes to an additional drag to the airplane during forward cruising mode. While in hovering mode, the drag penalty in not significant due to the short duration of the hovering phase. Most of the flight phase of the VTOL aircraft is in forward cruising mode. Thus, it imposed a significant increase of drag while in forward flight. The ability to characterized the drag introduced from the installation of VTOL components and structure is important in order to design an aerodynamically efficient aircraft. The VTOL structure and component adds to the total parasitic drag of the aircraft. The additional VTOL components used are arms, electric propulsion system and the propellers. Each of this components adds different drag value to the aircraft. While it seems that making smaller and shorter parts is the better option in reducing drag, there will be a point of conflict where the smaller propulsion system size would not be able to lift the aircraft.
Challenges in developing VTOL aircraft lies within its flight control, stability and endurance which is of prime area of research presently in this field [5]. As an example, study by Aoki and Muraoka [6] explores the design of forward wingtip to reduce induced drag of a VTOL aircraft. Another study by Footohi et.al [7] found that, for a VTOL aircraft, a sweptback tailless design provides better performance in comparison to conventional fixed-wing aircraft with a tail.

To increase performance of an aircraft, its drag needs to be reduced. Drag is categorized into two groups which are Parasitic drag and Induced drag [8]. Parasitic Drag is a combination of Form Drag, Interference Drag and Skin Friction Drag. In terms of reducing drag of the VTOL components and systems, various approaches have been recommended. For example, the parasitic drag of propeller in horizontal flight can be reduced by using folded propeller. From the study conducted by Goetten et. al [9], it is found out that individual aircraft design needs specific countermeasure to reduce its drag. Thus, study by Stahl [10] try to reduce drag contributed by the exposed VTOL motors to increase the aircraft performance. Some other researcher such as [11] use the deflected slipstream technology to improve the VTOL efficiency while study by Teo, [12] explorers on propeller blade design to be used specifically for VTOL application.

Thus the objectives of this research are to investigate the drag contributed by the vertical lifting propeller with various diameter, pitch and airspeed.

2. Drag of VTOL Aircraft

It is important that the drag force on the aircraft is minimized to ensure high efficiency of the aircraft. The drag force, \( D \) on an aircraft is given by:

\[
D = 0.5 S \rho C_D V^2
\]  

(1)

where \( S \) is the area of the wing, \( \rho \) is the air density, \( C_D \) is the coefficient of the drag and \( V \) is the aircraft velocity. In addition to the drag induced by the wings of the aircraft, a VTOL aircraft also suffers from drag due to the vertical lifting propulsion system therefore the drag coefficient consists of summation of the following 2 components:

\[
C_D = C_{D,i} + C_{D,o}
\]  

(2)

where \( C_{D,i} \) is the lift-induced drag coefficient while \( C_{D,o} \) is the zero-lift induced drag coefficient which is the parasitic drag. Induced drag is affected by the geometry of the wing and is given by [10]:

\[
C_{D,i} = \frac{C_L^2}{(\pi A \epsilon)}
\]  

(3)

where \( C_L \) is the lift coefficient, \( A \) is the wing’s aspect ratio and \( \epsilon \) is the Oswald efficiency number. If the wingspan is given by \( d \) and the area of the wing is \( S \), the wing’s aspect ratio, can be computed from the following [13] :

\[
A = d^2 / S
\]  

(4)

This equation shows that the induced drag increases with increasing wing area. Furthermore, the hover rotors of the VTOL aircraft introduce additional drag in which is categorized as a parasitic drag and relates to the viscous effects of the aircraft. This parasitic drag comprises of pressure drag, friction drag, interference drag and rotor shaft drag [10].
3. Methodology

3.1. Propeller selection

There are many propellers available off the shelf components which have various size, pitch and shape. As the purpose of the vertical propeller is to provide lift in hovering phase only, a high static thrust type of propeller which have low pitch were chosen. Propeller size from 5 inch to 9 inches was chosen due to the suitability of the chosen airframe. Table 1 shows the selection of propeller used in this research. There are 26 propellers with various diameter, pitch, number of blade and material.

Table 1. Propellers sample data.

| Prop number | Diameter (inch) | Pitch (degree) | Number of blade | Material   |
|-------------|----------------|----------------|-----------------|------------|
| 1           | 5.0            | 3.0            | 2               | EP         |
| 2           | 5.0            | 4.5            | 3               | Nylon      |
| 3           | 5.0            | 4.5            | 2               | Carbon     |
| 4           | 5.0            | 4.5            | 2               | Nylon      |
| 5           | 5.5            | 5.0            | 2               | EP         |
| 6           | 5.0            | 5.0            | 2               | EP         |
| 7           | 5.0            | 5.0            | 2               | Carbon     |
| 8           | 6.0            | 5.0            | 2               | Carbon     |
| 9           | 6.0            | 4.0            | 2               | Carbon     |
| 10          | 6.0            | 4.5            | 2               | Nylon      |
| 11          | 6.0            | 4.5            | 2               | Nylon      |
| 12          | 7.0            | 4.5            | 2               | EP         |
| 13          | 8.0            | 4.5            | 2               | Nylon      |
| 14          | 8.0            | 4.5            | 2               | Carbon     |
| 15          | 8.0            | 4.5            | 2               | Carbon     |
| 16          | 8.0            | 6.0            | 2               | EP         |
| 17          | 8.0            | 6.0            | 2               | EP         |
| 18          | 9.0            | 4.5            | 2               | Carbon     |
| 19          | 9.0            | 4.5            | 2               | Carbon fibre |
| 20          | 9.0            | 6.0            | 2               | EP         |
| 21          | 9.0            | 6.0            | 2               | EP         |
| 22          | 9.0            | 4.7            | 2               | Nylon      |
| 23          | 9.0            | 4.5            | 2               | Carbon fibre |
| 24          | 9.0            | 4.7            | 2               | Carbon     |
| 25          | 9.0            | 5.0            | 2               | Carbon     |
| 26          | 9.0            | 4.5            | 2               | Nylon      |

Propeller is measured by their diameter and pitch. The pitch is the theoretical distance travelled, by the prop, in one revolution. It is also the steepness of the angle of the blades. A low-pitch propeller will make less thrust and generally be more efficient. A high-pitch prop will make more thrust and generally draw more current from the battery.

Figure 1 shows the propeller sample used for this research. In general, the diameter of the propeller influences the amount of thrust generated. For a similar static thrust, a larger diameter prop rotates at slower speed thus generates less noise.

Figure 1. Propeller samples used for the wind tunnel test.
3.2 Wind tunnel setup and measurement

The wind tunnel experiment was conducted in the open circuit subsonic wind tunnel available in UniKL MIAT. This wind tunnel can operate at maximum airspeed of 40m/s. Figure 2 shows the subsonic wind tunnel and its control panel for the experiment.

![Figure 2. Subsonic wind tunnel and its control panel.](image)

The test section of the wind tunnel measures of 30cm x 30cm x 30cm as shown in Figure 3. The propeller was mounted horizontally as they would be mounted on the VTOL UAV. Since each of the chosen propellers have different pitch and diameter, measurements were taken by replacing the propellers attached to the motor inside the wind tunnel test section. The assembly of the motor and propeller are mounted on the force balance equipment within the test section. This force balance equipment which are attached to a load sensor enables the drag to be measured in Newton (N).

![Figure 3. Subsonic wind tunnel test section and test setup arrangement for propeller.](image)
4. Results

Each of the propeller sample was tested by varying the airspeed and the resultant drag value was recorded. The airspeed used were 10m/s, 12m/s, 14m/s, 16m/s, 18m/s and 20m/s. These airspeeds were chosen because the UAV is intended to be flown within these airspeed constraints. The propeller samples were arranged such that the propeller diameter is increased from 5 inch for sample 1 to 9 inch for sample 26. Figure 4 shows the result from the test. It can be seen from Figure 4 that the amount of drag produced is directly proportional to the propeller diameter size. A bigger diameter propeller has higher drag compared to smaller diameter propeller. This is due to the bigger frontal area exposed to the wind. The experimental data also coincide with Equation (1) where as airspeed is increased, the drag will also increase proportionally. As a result, an optimal selection for propeller diameter is chosen with the smallest possible diameter that could provide an adequate thrust for the UAV.

Figure 4. Propeller sample and its horizontal drag with different airspeed.

There are three factors that influence the drag produced by the placing the propeller horizontally facing the wind, which are propeller diameter, airspeed and blade pitch of the propeller. The first factor, as the propeller diameter increases, the amount area exposed to the wind is also increases thus increasing the drag. Figure 5 indicates an increase in drag as the propeller diameter increases.
The second factor that affects the amount of drag is the airspeed. As shown in equation (1), the drag increase as a factor of velocity squared. As shown in Figure 5, each propeller produced an increasing drag values as the airspeed increased. Furthermore, as the blade pitch of the similar diameter increases, the area that is exposed to the incoming air is also increase, thus increasing the drag. For example, a 5 inch propeller, with pitch of 3, 4.5 and 5, as the value of pitch increase, the resultant drag also increase.

A detailed graphs showing the relationship between blade pitch propeller diameter and airspeed for each similar propeller diameter is shown in Figure 6. It shows an interesting result that as the airspeed is increased, the intermediate blade pitch has higher drag compared to higher blade pitch. For example, a 5 inch propeller tested in 20 m/s airspeed, a propeller with blade pitch of 5 has lower drag compared to a propeller that has blade pitch of 4.5. This trend also can be seen from propeller with 6 inch and 9 inch. The same condition can also be observed for 9 inch propeller as the pitch change from 5 to 6, the amount of drag is reduced nearly half. This finding requires further analysis since the drag should increase linearly with increasing pitch. Thus, details study is planned for future works.
5. Conclusion
In contrast to other studies in which the air flow is in line with propeller shaft, this paper presents the drag produced by placing the propeller horizontally. This is to replicate the condition of a SLT VTOL aircraft where the propeller is exposed to the incoming air during forward cruising phase. For these vertical propellers, three factors affect the amount of drag produced which are propeller diameter, blade pitch and airspeed. 26 propeller samples were tested in wind tunnel facilities and data for each propeller was analyzed. From the data gathered, the least drag from all the tested propellers was those that are smallest in diameter with lowest pitch blade. As the airspeed plays an important factor in drag produced, lower forward speed is desirable to reduce the drag form the propeller. The result from these analysis is important for making a decision for optimum selection of motor and battery for the VTOL propulsion system.

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