Aerodynamic Analysis of Hybrid Drone

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Abstract. Drones are Unmanned Aerial Vehicles (UAV’s) or Remotely Piloted Vehicles (RPV’s) whose application ranges from photography to defence. There are two major classifications of drone, one, a fixed wing; and another, a quadcopter. A hybrid drone is a kind of drone which has a mix of features of the two kinds of drone. It has quad-rotors for Vertical Take-Off Landing (VTOL), and a fixed wing for cruise. Aerodynamic analysis for a hybrid drone is done using Computational Fluid Dynamics (CFD) as a tool. A virtual wind tunnel test is done by means of this analysis. It is done in order to examine the various technical edges of the hybrid drone over the rest of the types. Firstly, the main entity of the drone, the wing, of 3 different profiles(aero-foils), is analysed for better lift coefficient as it is the major contributor for the thrust during cruise (for 0 deg angle of attack). The velocity contours are viewed to interpret the aerodynamic advantage of each wing. Then the whole vehicle is analysed after inculcating the wing. The various aerodynamic parameters such as the lift force, lift coefficient, drag force and drag coefficient of the hybrid drone are determined from the analysis. A hybrid drone with optimum lift has been designed from the inference.

Keywords: Unmanned Aerial Vehicles (UAV’s) or Remotely Piloted Vehicles (RPV’s), Vertical Take-Off Landing (VTOL), Computational Fluid Dynamics (CFD), angle of attack, aerodynamics, lift, drag.

1. Introduction

UAVs (Unmanned Aerial Vehicles) or Remotely Piloted Vehicles, are aircrafts without human pilot or personnel operating it onboard. It is either controlled by an operator by the virtue of a wireless remote, or a fully autonomous flight with controllers on-board with algorithms for navigation.

There are three main classification of drones, namely;

- Quad (or multi)-rotor drone
- Fixed wing drone
- Single-rotor drone

1.1. Problem Encountered

Drones are employed in various applications, but there are notable and practical limitations for the same. In medical field, the transportation of organs, blood, etc, in various geographies of the world,
employ drones. The major problem here is that fixed wing drones are used, owing to the advantage of having good stability and range, whereas having the limitation that the drone cannot be landed or hovered in any location.

Moreover, in defence field, quadcopters are employed in surveillance, and emergency situations such as, rescue operations during natural calamities as they possess VTOL (Vertical Take-off Landing) feature. But due to unstable nature of this type of drone and lower operation range, its application is less effective and less efficient too.

1.2. Quad (or multi)-Rotor Drone
It’s a type of drone that has rotors on the corners of its structure (frame) as shown in figure 1., which are coupled with propellers, that produce lift and the thrust required for the flight. It has VTOL (Vertical Take-Off Landing) feature in it. The disadvantage part of it is that it has lower range and lesser stability during cruise.

![Figure 1. Quad-rotor drone; Succo; “Spying quadcopter: espionage and observation”; 2014; Pixabay](https://commons.wikimedia.org/wiki/File:Spying_quadcopter.jpg)

1.3. Fixed Wing Drone
It’s similar to a normal flight in working but is e-propelled most of the times. Unlike the other types, it has wings to produce lift as shown in figure 2. and a propeller with horizontal axis of rotation to move forward. The major disadvantage is the requirement of run way for take-off and landing.

![Figure 2. Fixed-wing drone; Ssgt Reynaldo Ramon; “IAI Heron 1 UAV in flight”; 2003; Wikimedia Commons;](https://commons.wikimedia.org/wiki/File:IAI_Heron_1_in_flight_2.JPEG)

1.4. Single-Rotor Drone
Its functionality is similar to that of a usual helicopter, with a single central rotor with vertical axis of rotation as depicted in figure 3. Again, the disadvantages of low stability and complex operation makes it a less preferred model.
1.5. Proposed solution

In order to overcome the disadvantages of quadcopter and fixed wing drone, a hybrid drone is proposed as shown in figure 4. A hybrid drone is a combination of a quad-copter and a fixed wing drone. It takes the advantage of VTOL from quad and a stable cruise journey from fixed wing. This type of drone is still under R&D and study.

![Diagram of hybrid drone]

1.6. CFD Deployment

Computational Fluid Dynamics (CFD) is used to predict the nature of fluid flow. Here, it is deployed to find the aerodynamic parameters of the wing and the hybrid drone, such as the lift force, drag force, lift coefficient, and drag coefficient. Using CFD as a tool, the flow characteristics, velocity contours are obtained.

1.7. Governing Equations

i. Continuity Equation:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \]

ii. General Transport Equation:

\[ \frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho \mathbf{V} \phi) = \nabla \cdot (D \nabla \phi) + S \]

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**Figure 3.** Single-rotor drone; Wesha; “E-flite Blade mSR (Micro Single Rotor) remotely controlled model helicopter”; 2010; Wikimedia Commons; [https://commons.wikimedia.org/wiki/File:E-flite_Blade_mSR_Micro_Single_Rotor_Model_Helicopter_3.jpg](https://commons.wikimedia.org/wiki/File:E-flite_Blade_mSR_Micro_Single_Rotor_Model_Helicopter_3.jpg)

**Figure 4.** Hybrid drone Explanation.
iii. X-Momentum Equation:
\[ \frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho V u) = \nabla \cdot (\mu \nabla u) - \frac{\partial p}{\partial x} + S_u \]

iv. Energy Equation:
\[ \frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho V h) = \nabla \cdot \left( \frac{k}{C_p} \nabla h \right) - \frac{\partial p}{\partial x} + S_h \]

v. Species Transport Equation:
\[ \frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho Y_i V) = \nabla \cdot (D_i \nabla Y_i) - \frac{\partial p}{\partial x} + R_i \]

2. Literature Review

Uğur C. Yaylı et al., says about optimization of fixed wing aircraft in order to reduce the take-off/landing distance. The lift, drag, velocity (air) and various parameters are observed by changing the airfoil used for wing, tail configuration, fuselage design. This is similar to our project, except for the fact that the analysis is performed on fixed wing [1]. Pooneh Aref et al., discusses about the aircraft wing’s aerodynamic characteristics with and without propellers using CFD as a tool. The local lift, drag coefficients are found considering four cases at a time, without propeller, with propeller (inboard)(ccw), (cw) and with propeller (outboard)(ccw). The variation in the parameters are plotted in a graph for comparison and the best case is found [2]. Dhwanil Shukla et al., says about the aerodynamic analysis of a multi-copter. Specifically, he discusses about the consequences pertaining to the interaction between two adjacent propellers and its effect on performance. Blade–vortex interaction is stated as the reason for the hinderance of performance [3]. K Sreelakshmi et al., says about aerodynamic analysis of UAV and finding the lift and drag forces for a fixed wing drone. The results in the form of plots are made using Ansys software [4]. Piotr Kardasz et al., discusses about the limitation of commercial drones being dependent on battery for power. Also discusses about the hinderance due to battery failure, breakdown, obstacle collision, etc. He also adds upon to the research on batteries and various other new power sources for drones [5]. Chun Fui Liew et al., summarizes the different types of UAVs and their features. Specifically, it gives a brief note on research activities pertaining to UAVs from the year 2001 [6]. Hazim Shakhatreh et al., discusses the various challenges relating to UAVs such as battery-related problems, collision and other scopes of research in UAVs. It also briefly upon the civil infrastructure development and the related challenges [7].

Oscar Vestlund says, the battery powered UAVs limits the powered time and poses the need to design a UAV with extended flight time. This study investigates the possibility of designing a large VTOL UAV which is capable of a higher range. Design with high lift to drag ratio is achieved and the best VTOL type is suggested based on the aerodynamic and structural analysis [8]. Özgür Dündar et al., discusses the Fixed Wing Drone and the Hybrid drone in terms of their endurance capabilities. It comprises the power and energy requirements to achieve the maximum endurance during cruise, climbing and landing and the best type is suggested for the prominent application [9]. Ventura Diaz et al., discusses about CFD analysis of three different multirotor drones. The analysis of drones is done with different rotors and for various weather conditions. A comparative study is done for various configurations [10]. K Christodoulou et al., discusses finding the aerodynamic parameters of a propeller, which is incorporated in a drone, made from scratch. It is found through CFD analysis using three different turbulence models, and the appropriate design for the propeller is selected from the results [11]. Vasilie Prisacariu et al., says about numerical analysis of a UAV wing for various angles of attack and stresses the requirement of wind tunnel experiments to confirm the results of the CFD analysis done [12]. C T Lao et al., discusses the effects of ground-effect on the lift, performance, and various aerodynamic parameters of the wing. He adds that it improves lift, performance and Oswald efficiency, while producing an inconsistent moment coefficient [13]. Khuntia SK et al., says about the optimization of design of a wing for better efficiency using the outcomes of CFD analysis of the same. It is achieved through analysis of iterative designs of wings using ANSYS software. In addition, the strength of the wing is also analyzed using the same software and by comparison it is found to be
advantageous than the traditional wing in load carrying capacity and various other parameters [14]. Zhe Ning discusses the aerodynamic parameters pertaining to the wake structure of the propellers. In addition, a couple of bio-mimicked propellers have been analysed for aerodynamic performance and acoustic advantages [15].

3. Parts of a hybrid drone

3.1. Frame
It is the main part of the drone, to which all the other components are joined. It is selected based on the size, load, and various dynamic requirements. There are many types of frames, namely,
1. X-type frame
2. H-type frame
3. Z-type frame
4. Plus-type frame

3.2. Wing
Wing is the major contributor for lift of the drone. In a hybrid drone, the wing plays a major role in counteracting for the weight and propelling the drone during the cruise. The wing contains ailerons, flaps to control the lift parameters to greater extent.
The basic unit of a wing is the aero-foil, from which it is extruded. The aerodynamic parameters of the aerofoil are the most important in determining the type of the wing. The main features that determine the properties of wing are:
- Aero-foil:
  - Aero-foil is the basic entity of a wing, which forms the cross-section of the same.
- Wing Planform:
  - It refers to the shape of the wing from top-view after its being extruded.
  - Classified as Straight wing, Swept wing, and Delta wing.

3.3. Fuselage
In an UAV, it is the part which houses all the hardware parts of the drone, such as battery, ESC, flight controller board, receiver, etc. It is basically the covering of the hardware components of the UAV (drone). It adds to the major weight of the drone as it contains the hardware components.

3.4. Tail
It is the component that helps in controlling the direction of the UAV. This is again an aero-foil, which is extruded to form the tail.

4. Design calculation for drone
During Cruise flight, the following conditions are considered:

Steady Flight + Level Flight
\[
\left(\frac{dV}{dt} = 0\right) \quad (\gamma = 0)
\]
(Constant Vel) (No inclination w.r.t horizontal)

Now, the following values are considered for finding the required parameters,

Weight (Structure, payload, battery) = 1kg
Velocity of wind = 10m/s
Chordal length = 0.2m
Kinematic Viscosity=1.5*e-5 m²/s
Density of Fluid medium(air)= 1.225 kg/m³
4.1 Lift - Coefficient Calculation
Now, the Reynold’s Number is found for further calculations:
\[
\text{Reynold’s Number } = Re = \frac{V \times l}{v}
\]
\[
= 10 \times 0.2 / (1.5 \times e^{-5})
\]
\[
= 1,33,333.
\]
(Here ‘l’ is the Chordal length of aero foil in ‘m’)

Figure 5. Aero-foil Demonstration (Free Body Diagram); Adapted from Grahamuk; “Graphic of aerofoil cross section”; 2013; Wikimedia Commons https://commons.wikimedia.org/wiki/File:Aerofoil.svg

From the figure 5., it is clear that
\[
=> \text{Thrust} = \text{Drag} \tag{1}
\]
\[
=> \text{Lift} = \text{Weight} \tag{2}
\]
From Eq. (2), we get, W=L;
\[
\Rightarrow W = \frac{1}{2} \rho \times S \times V^2 \times C_L \ \left( \text{since } L = \frac{1}{2} \rho \times S \times V^2 \times C_L \right) \tag{3}
\]
Rewriting the above, we get:
\[
\Rightarrow C_L = \frac{2 \times W}{\rho \times S \times V^2} \tag{4}
\]
Now, to find Area(S), take Aspect Ratio (for low speed drones) = 12.5
w.k.t., \(A.R(\text{Aspect Ratio}) = \frac{b^2}{S} \Rightarrow 12.5 = \frac{b^2}{b+c} \)
\[
\Rightarrow b = 12.5 \times 0.2 = 2.5m
\]
Now, \(S(\text{Area}) = b \times C = 2.5 \times 0.2 = 0.5m^2, [\text{for rectangular planform}]\)
where, \(b\)-span of the aerofoil in m,
\(C\)-Chordal length or characteristic length in m

Substitute ‘S’ in Eq. (4), we get:
\[
\therefore (C_L)_{req} = 2 \times (1 \times 10/0.5) / (1.225 \times 10^2) = 0.3265
\]

4.2 Minimum Thrust Calculation
Consider, Eq. (1) ÷ Eq. (2):
\[
=> \frac{T}{W} = \frac{D}{L}
\]
\[
=> T = D \times W / L = W / (L/D) \tag{5}
\]
Note:
\[
L = \rho \times \frac{A_v^2}{2} \times C_L \tag{6}
\]
\[
D = \rho \times \frac{A_v^2}{2} \times C_d \tag{7}
\]
Where,
\( A = \text{Area in } \text{m}^2 \),
\( V = \text{Velocity in } \text{m/s} \),
\( \rho = \text{Density in Fluid in } \text{kg/m}^3 \).
\( C_L = \text{Lift Coefficient} \).
\( C_d = \text{Drag Coefficient} \).

Putting Eq. (6) and (7) in Eq. (5), we get,
\[
T_{\text{min}} = \frac{W}{\left( \frac{C_L}{C_d} \right)_{\text{max}}} \quad (8)
\]

To find maximum value of \( \frac{C_L}{C_d} \), consider,
\[
\frac{d((C_L/C_d))}{dC_L} = 0
\]
we know that,
\[
C_d = C_{d_0} + KC_L^2 \quad (9)
\]
Where,
\( C_{d_0} = \text{Drag Coefficient, when } \alpha = 0 \)
\( K = \frac{1}{\pi eAR} \)
\( e = \text{Oswald efficiency} \)
\( AR = \text{Aspect ratio} = \frac{b^2}{S} \)
\( b = \text{Span length} \)
\( S = \text{Area} \)

Again,
\[
\Rightarrow \frac{d((C_L/C_d))}{dC_L} = 0
\]
\[
\Rightarrow \frac{C_{d_0} + KC_L^2 - C_L(2KC_L)}{C_d} = 0
\]
\[
\Rightarrow C_{d_0} = \frac{KC_L^2}{C_d}
\]
\[
\therefore C_L = \frac{C_{d_0}}{\sqrt{K}} \quad (10)
\]

Now, substitute Eq. (10) in Eq. (9)
Therefore, we get,
\[
\therefore C_d = 2C_{d_0} \quad (11)
\]

Substitute Eq. (10) and Eq. (11) in \( \left( \frac{C_L}{C_d} \right)_{\text{maximum}} \)
\[
\Rightarrow \left( \frac{C_L}{C_d} \right)_{\text{maximum}} = \frac{C_{d_0}}{\sqrt{K}}
\]
\[
\therefore \left( \frac{C_L}{C_d} \right)_{\text{maximum}} = \frac{1}{\sqrt{4KC_{d_0}}} \quad (12)
\]

Substitute Eq. (12) in Eq. (8):
We get,
\[
T_{\text{min}} = W \times \sqrt{\frac{4KC_{d_0}}{4KC_{d_0}}}
\]
Here, \( k = 1/ (\pi \times 1 \times 12.5) = .0254 \), sub. in Eq. (13)
\[
\Rightarrow T_{\text{min}} = 1 \times 10 \times \sqrt{4 \times .0254 \times .02} = 0.45 \text{ N}
\]

5. Design of wing
Many standard aero-foils are available in NACA library as stated in the previous chapter. There are two kinds of aero-foils, symmetric and asymmetric. For the analysis one of symmetric type and two of asymmetric type are chosen. Here, 3 aerofoils, namely, NACA 0012 (symmetric), NACA 6409 (asymmetric), and NACA 6412 (asymmetric), are considered for comparison and the best aero-foil with optimum Cl to Cd ratio is taken for designing the hybrid drone.
5.1. NACA0012
The various characteristics of the aero-foil are (as depicted in figure 6. and figure 7.):
   Max. camber = 0%
   Max. camber position = 0%
   Thickness = 12%

![Figure 6. NACA0012 Profile.](image)

![Figure 7. NACA0012 wing.](image)

5.2. NACA6409
The various characteristics of the aero-foil are (as depicted in figure 8. and figure 9.):
   Max. camber = 6%
   Max. camber position = 40%
   Thickness = 9%

![Figure 8. NACA6409 Profile.](image)

![Figure 9. NACA6409 wing.](image)

5.3. NACA6412
The various characteristics of the aero-foil are (as depicted in figure 10. and figure 11.):
   Max. camber = 6%
   Max. camber position = 40%
   Thickness = 12%

![Figure 10. NACA6412 Profile.](image)

![Figure 11. NACA6412 wing.](image)

6. Aerodynamic analysis of wing
The aerodynamic analysis is done to select the wing with best lift coefficient to drag coefficient ratio, and optimum lift coefficient for the specific condition considered. The analysis is done using
Converge CFD software for the above initial and boundary conditions. The initial conditions specify the values of physical variables during the start of the simulation, i.e., when time, $t=0$ s. The boundary conditions specify the values of the physical variables in the inlet, outlet, and various walls. The initial and boundary conditions are as follows:

- Reynolds Number ($Re$) = $1.33e+05$
- Fluid Medium = Air
- Kinematic Viscosity ($\nu$) = $1.52e-05$ $m^2/s$
- Angle of Attack ($\alpha$) = 0 deg
- Temperature ($T$) = 20 deg Celsius
- Velocity ($V$) = 10 m/s
- Pressure ($P$) = 1 atm (101325 Pa)

The grid independence test has been done, considering the system constraints, it is found that $0.01m \times 0.01m$ mesh is optimal with Adaptive Mesh Refinement around the aerofoil surface of 5 levels of embedding. The $k-\omega$ SST turbulence model is selected as it is external flow and it is advantageous as it switches between the equations it solves for lower $Y+$ value (in Viscous sub-layer) and higher $Y+$ value (turbulence layer).

6.1. NACA0012

**Figure 12.** below shows that the velocity distribution is symmetrical about the chord, since the aerofoil is symmetric. This is the cause of the negligible lift coefficient as the forces in the top and the bottom cancel each other. **Figure 13.** shows that the lift coefficient is very much lower ($0.019\sim0$) than drag coefficient (0.157), since it is a Symmetric Aerofoil. This value very much lesser than the required value of lift coefficient ($Cl_{req}=0.33$). **Figure 14.** shows the lift to drag coefficient ratio. The $Cl/Cd$ ratio is an important factor for finding the aerodynamic parameters of an aerofoil. The value converges to 0.125 for this case, which is very negligible.

![Figure 12. NACA0012 Velocity contour.](image)

![Figure 13. NACA0012 Lift and Drag Coefficient.](image)

![Figure 14. NACA0012 Cl/Cd ratio.](image)

6.2. NACA6409
Figure 15. below shows that the velocity distribution is not symmetrical about the chord, since the aerofoil is asymmetric. The velocity below the aero-foil is lower as compared to upper side. Hence the pressure below the aero-foil is far higher than the upper side, which offers higher lift. Figure 16. shows that the lift coefficient is very much higher (1.27) than drag coefficient (0.032). This value is amply greater than the required value ((C_l)req=0.33), which is recommendable. Figure 17. shows the lift to drag coefficient ratio. The value converges to 38.9 for this case, which is optimal.

Figure 16. NACA6409 Lift and Drag Coefficient.

Figure 17. NACA6409 Cl/Cd ratio.

6.3. NACA6412

Figure 18. below shows that the velocity distribution is not symmetrical about the chord, since the aerofoil is asymmetric. This shows that the velocity in the leeward side of the aerofoil is considerably lower than that in the upper and lower regions. This causes higher drag coefficient. Figure 19. shows that the lift coefficient is lower (0.079) than drag coefficient (0.562). This value much lesser than the required value of lift coefficient ((C_l)req=0.33). Figure 20. shows the lift to drag coefficient ratio. The average value of the trend converges to 0.14 for this case, which is negligible.

Figure 18. NACA6412 Velocity contour.
6.4. Comparison of Simulation

Here 1-NACA0012, 2-NACA6409, 3-NACA6412. Table 1, shows that the Cl/Cd ratio is optimal for Aero-foil-2, i.e., NACA6409. The plot, figure 21, shows that the lift coefficient is higher and drag coefficient is lower for Aero-foil 2, i.e., NACA6409, so it is recommended for the wing. The plot (figure 22.) shows that the Cl/Cd ratio is optimal for Aero-foil-2, i.e., NACA6409, so it is selected for the wing.

### Table 1. Comparison of Aerodynamic parameters.

| Sl. No. | Aero-Foil     | Lift Coefficient | Drag Coefficient | Cl/Cd  |
|---------|---------------|------------------|------------------|--------|
| 1       | NACA 0012     | 0.019            | 0.15             | 0.125  |
| 2       | NACA6409      | 1.27             | 0.032            | 38.9   |
| 3       | NACA6412      | 0.0797           | 0.56             | 0.144  |

7. Design of hybrid drone

The wing is incorporated in the drone design, the various views of the same are as shown below. Figure 23, shows the front view of the drone and exposes the frontal area of the same. Figure 24, shows the top view of the drone, describing the planform of the wing and the rotor positioning. Figure 25, shows the side view of the drone, describing the fuselage design in detail. Figure 26, shows the dimensions of the drone, conforming to the one, when it would be fabricated. Figure 27, shows the isometric view of the drone in a rendered fashion.
Figure 24. Top View.  
Figure 25. Side View

Figure 26. Dimensions of the drone.  
Figure 27. Isometric View.  

8. CFD analysis of hybrid drone  
Figure 28. and Figure 29. show that the velocity pattern is similar to that of the wing, which plays a major role in the aerodynamic parameters of the drone. The velocity in the leeward side is much lower (~0), which accounts for the drag. This low velocity region, which causes the drag, is due to the flow separation accorded to the geometry of the drone. There are various other parameters which do affect the drag formation. They are:

- Wake formation in the leeward side.
- Higher pressure gradients in the leeward side of the geometry, i.e. drastic variation of pressure due to partial vacuum in the critical region and high pressure in the region away from it.

As the flight is considered for cruise operation only the above parameters are taken into concern. The parameters like angle of attack, etc., are not taken into consideration due to the nature of application. Thus, the analysis on the drone body has been done.
Figure 28. Velocity contour front view.

Figure 29. Velocity contour side view.

9. Conclusion
The aerodynamic analysis of various wings, the major contributor for the lift of the hybrid drone, was carried out and the solutions converged (reached steady state). The best lift to drag coefficient ratio (38.9) offering wing, i.e., NACA6409, was selected for the drone for operation during the cruise condition and incorporated on the same. The hybrid drone was analysed and the results converged to an optimum value. As the results were favourable, a prototype model was made by 3D printing using PLA (Poly Lactic Acid) as material. A new type of drone with hybrid characteristics has been designed and tested for aerodynamic properties, and the advantages were recorded.

The project has a wide scope as it involves an upcoming technology in it. The future scope would be to develop a test-prototype to perform wind tunnel test and ascertain the simulation results. Then develop an original model for the hybrid drone and test its practical functionality. After tuning its dynamic functionalities, the drone would be further developed for applications such as air-ambulance service, surveillance, defence applications, etc.
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