CP 301: DEVELOPMENT ENGINEERING PROJECT

A REPORT ON PARTIAL FULFILMENT OF DESIGN AND DEVELOPMENT OF FLYING ELECTRIC VEHICLE

Submitted By:-

Ankur Kumar (2022eeb1154)
Ansh Raj (2022eeb1155)
Abbas Ali (2022eeb1146)
Sonu Koli (2022eeb1215)

Under the supervision of:-

Dr. Saifullah Payami

Department of Electrical Engineering
Indian Institute of Technology, Ropar

May 2025

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ACKNOWLEDGEMENT

We are expressing our sincere appreciation to **Dr. Saifullah Payami** for providing us with the opportunity to work on this ongoing project. His continuous support, guidance, and encouragement have been instrumental in helping us navigate the different stages of our work. His expertise and patience have made the learning process more engaging and productive.

Dr. Payami's constructive feedback and insightful suggestions have significantly enhanced our understanding of the subject and helped us improve the quality of our work. His mentorship has not only contributed to our technical skills but has also strengthened our ability to approach problems critically and work collaboratively as a team.

We are truly grateful for the chance to learn and grow under Dr. Payami's supervision. This experience is enriching our academic journey, and we look forward to continuing our work under his valuable guidance and support.

INTRODUCTION

In our project, we are designing and developing a compact electric Vertical Take-Off and Landing (eVTOL) air taxi prototype, capable of lifting a payload of up to 5 kg. eVTOL technology represents a new frontier in aerial mobility, combining the benefits of electric propulsion with the versatility of vertical takeoff and landing. These aircraft eliminate the need for runways and aim to reduce urban congestion by enabling point-to-point travel in densely populated areas. One of the key advantages of eVTOLs is their potential for lower noise, zero in-flight emissions, and higher mechanical efficiency, making them ideal candidates for urban air mobility (UAM) solutions.

Our eVTOL prototype employs high-speed Brushless DC (BLDC) motors as the primary propulsion units, chosen for their excellent torque-to-weight ratio, high efficiency, and reliability. These motors are driven using sinusoidal Pulse Width Modulation (PWM) techniques implemented on an FPGA-based controller. The electrical drive system consists of inverters and DC-DC converters that efficiently manage power distribution from the DC power supply to the motors. These converters are designed with considerations for weight, thermal performance, and switching losses, which are critical factors in aerial platforms where every gram and watt count. To convert electrical energy into useful thrust, we use aerodynamically efficient propellers, selected based on blade geometry, pitch, and diameter to match the specific motor performance characteristics. This ensures that we achieve maximum lift-to-power efficiency, a crucial metric in VTOL flight where hover efficiency dominates.

Overall, our goal is to develop a functional and scalable eVTOL prototype that demonstrates the core principles of electric air taxi operation using custom-built hardware and advanced control strategies. This project lays the foundation for future research into more complex flight control algorithms, battery integration, and autonomous navigation—key components of next-generation aerial mobility systems.

OBJECTIVE

- To select suitable propulsion components—including high-thrust BLDC motors, compatible ESCs/inverters, aerodynamic propellers, and an appropriate battery system—to enable vertical lift of a total mass of approximately 15 kg (comprising 10 kg vehicle body and 5 kg payload).

- To evaluate and match the motor-propeller-battery combination based on thrust-to-weight ratio, current and voltage requirements, and flight endurance, ensuring stable and efficient hover and maneuvering capabilities.

- To design and fabricate a lightweight yet structurally robust chassis, capable of supporting the propulsion system and electronics while minimizing overall weight and aerodynamic drag.

- To determine the optimal placement and spacing of the propellers (arm length and motor-to-motor distances) to reduce aerodynamic interference, ensure symmetric thrust distribution, and improve in-flight stability.

- To implement an efficient power electronics and control architecture, involving ESCs or custom inverters controlled via sinusoidal PWM signals generated through an FPGA or microcontroller-based system.

- To develop and integrate a basic control system for flight stabilization, including motor speed control for pitch, roll, yaw, and altitude regulation—paving the way for more advanced autonomous control in future phases.

THEORY

Power Source:- LiPo Battery as DC Power Supply

Reference:- [LiPo Batteries]

Lipo is a rechargeable battery of lithium-ion technology using a polymer electrolyte instead of a liquid one. High-conductivity semi-solid polymers form this electrolyte. These lipo batteries provide a higher specific energy than other lithium-battery types. It is a newer type of battery now used in many consumer electronics devices and has gained popularity over the last few years.

Cell Configuration:-

A battery is constructed from rectangular cells that are connected to form the battery. A cell, which can be considered a battery in itself, holds a nominal voltage of 3.7V. By connecting more of these in series, the voltage can increase to 7.4V for a 2-cell battery, 14.8V for a 4-cell battery, and so on. By connecting more batteries in parallel, the capacity can be increased.

Often, one will see numbers like 4S2P, which means the battery has 4 cells (4S) connected in series, and there are 2 cell sets connected in parallel (2P), giving a total number of 6 individual cells in the battery. So the number of cells is what defines the voltage of the battery.

Having a higher voltage means the battery can provide more power to drive bigger motors, however, more power does not necessarily mean the battery will provide energy for longer, that is defined by the battery capacity.

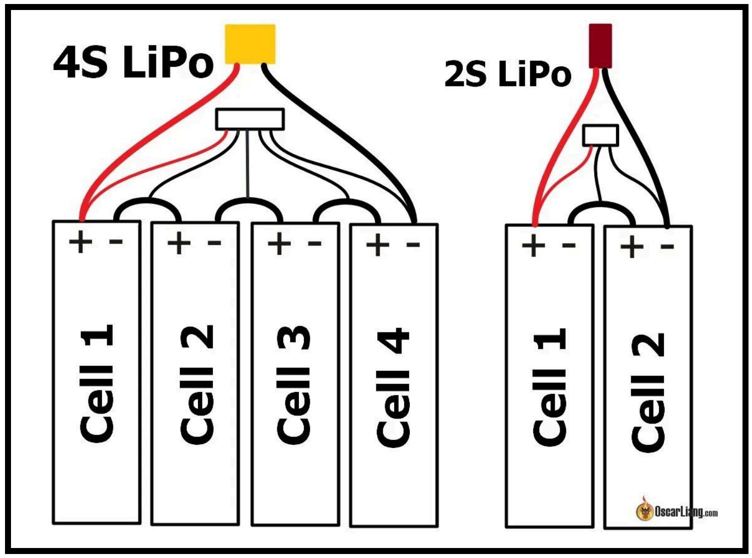


Fig.:- Cell configuration of 4S (nom. Voltage: 14.8V) and 2S (nom. Voltage: 7.4 V) LiPo Batteries

Battery Voltage:-

A single LiPo cell has a nominal voltage of 3.7V; i.e.; 1 LiPo cell = 1 cell = 1S = 3.7V.
Ex. - Voltage of 6S = Net Voltage of 6 cells connected in series = 6*3.7 = 22.1V (approximately 22.2 V).

So, a motor having a rating of 370KV will spin at 370 rpm for every volt we apply to it. On a 6S rating battery, it will spin around 8200 rpm. Hence, the more voltage we have, the faster we are going to go.

Battery Capacity:-

Capacity is used to measure how much power a battery can hold and the unit of capacity is milliamp hours (mAh), which means, for example, a battery having capacity of 8000mAh will in 1 hour if the load connected to it draws a constant current (discharge current) of 1A continuously.

Generally, capacity can determine how long one can run before recharging. A larger capacity pack may give you longer flight times, but being heavier, it will adversely affect performance. But it is also influenced by the speed; the quicker you can fly your plane, the less time your flight takes. Because high speed means you need more power to drive your plane or others, so your power is lost quickly.

Discharge Rating:-

Discharge Rate ("C" Rating) is simply how fast a battery can be discharged safely. A battery with a discharging rate of 25C, that means one could safely draw it at 25 times more than the capacity of the pack taken in “Ah” units.
Example:- A battery having capacity of 8000mAh is discharging at a continuous rate of 25C ⇒ 25×8 Amp = 400A of discharging current is drawn from the source.

Sometimes, one would require a battery of high discharging rate, usually in a race, to get a higher burst in a moment. But the disadvantage of having a high “C” rating is that it may get heavier and affect the performance. Also, it may get more expensive than the lower one.
For our project, we will be needing a battery with a low discharge rate to get good time of flight.

Selected Voltage Source:- Pro-Range 22.2V 8000mAh 25C 6S Lithium Polymer Battery Pack

Motor Selection:- BLDC Motor

Reference:- BLDC Motor

Brushless DC Motor (BLDC)

A Brushless DC Motor (BLDC) is a type of permanent magnet synchronous motor powered by direct current (DC) electricity, using an electronically controlled commutation system instead of a mechanical one. Unlike brushed DC motors, BLDC motors do not use brushes or a mechanical commutator; instead, they rely on electronic controllers to switch current through the stator windings, enabling the rotor to generate continuous torque.

Construction :-

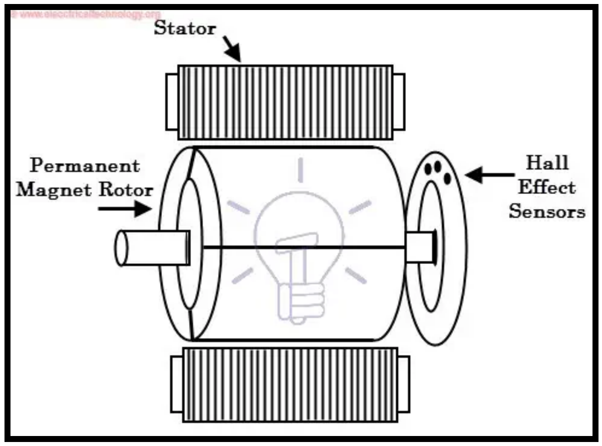


Fig.:- Typical construction of BLDC motor

In BLDC motors, the rotor consists of permanent magnets, while the stator contains stationary armature windings. The rotor position is detected using sensors such as Hall-effect sensors or rotary encoders, which allow precise timing for current switching. This ensures the magnetic fields remain in the correct orientation for efficient torque production, with the stator field maintained in quadrature to the rotor's magnetic field.

Working:-

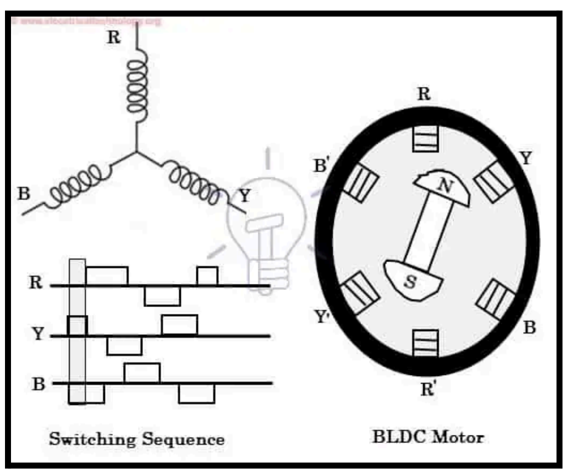


Fig.:- Generation of 3-phase Voltage output in a BLDC motor

A BLDC motor operates on the same fundamental principle as conventional DC motors, following Lorentz force law, which states that a current-carrying conductor in a magnetic field experiences a force. However, in a BLDC motor, the current-carrying conductors are fixed in the stator, while the permanent magnet rotor moves, creating a reverse interaction force that drives rotation.

When the stator windings are energized through controlled switching, they act as electromagnets, generating a magnetic field in the air gap. Although the supply is DC, electronic commutation creates a trapezoidal back-EMF waveform, which interacts with the rotor's magnetic field. The rotor rotates due to the combined effect of attraction (opposite poles) and repulsion (like poles) forces between the stator and rotor fields.

The motor's rotation relies on a precise sequence of stator coil energization, controlled by an electronic controller. This controller determines which windings to activate by using rotor position feedback from Hall-effect sensors or similar devices, ensuring the magnetic fields remain properly aligned for continuous rotation.

These Hall-effect sensors provide high and low signals as the rotor poles pass them, indicating the rotor's position. The controller uses this feedback to manage the switching sequence, ensuring efficient torque production and smooth operation of the BLDC motor.

Some Advantages:-

- High efficiency due to the use of permanent magnet rotor
- High speed of operation even in loaded and unloaded conditions due to the absence of brushes that limits the speed
- Smaller motor geometry and lighter in weight than both brushed type DC and induction AC motors
- Long life as no inspection and maintenance is required for commutator system
- Quiet operation (or low noise) due to absence of brushes

The absence of brushes results in reduced mechanical wear, lower noise, and higher efficiency—typically around 85-90%, compared to 75-80% in brushed DC motors. BLDC motors are widely used across various power ranges and are particularly suited for high-speed, high-efficiency applications.

KV rating of a BLDC motor:-

Reference:- KV rating

Theoretically KV represents the speed at which the motor rotates for every volt applied to the motor.

Example:- If we used 6S LiPo (22.2V) to power a 370KV motor, as in our selected motor, the maximum number of motor rotations would be approximately 370×22.2 = 8214 RPM.

Ideally, it would rotate at 34040 RPM without any load. In reality, there will always be some load- in the RC world, that would be propeller's and, due to the air resistance, the motor won't be able to reach that RPM, it will always be a bit lower.

Motors with a higher KV rating will be able to rotate the propeller faster. That means those with a lower Kv rating won't be able to do it as fast, but their torque will be higher. That's exactly why it's advised to have larger props combined with low KV motors. Higher Kv motors will be more efficient with higher RPM but at a cost of the torque.

For our project, we have selected a motor with 370KV rating, KV rating is relatively on the lower side, but large propellers with diameter of 17 inches to get the required torque, thrust and power.

Selected Motor:- Reflex Drive RD 1760 17-inch Folding Propeller with Hub – CW

Propellers as a load:-

The propellers of a quadcopter are its lifeline, acting as the "wings" that convert rotational energy into aerodynamic lift and thrust. Unlike fixed-wing aircraft, quadcopters rely entirely on the precise interplay of their four propellers to lift upward, downward, and stabilize. The geometry of these propellers is not arbitrary—it is a carefully engineered balance of shape, curvature, and structural design.

Construction:-

Reference:- Prop. Construction

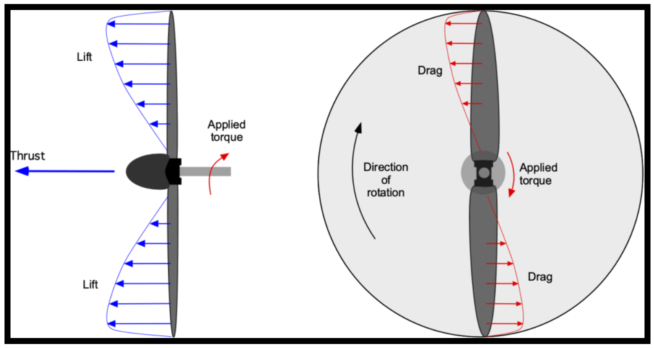


Fig.:- Production of net thrust by propeller due to applied torque at propeller shaft

Diameter of a propeller: It is the distance from one blade tip to the other that determines the total swept area of the rotor.

A larger diameter propeller moves a greater volume of air per revolution, which increases lift and thrust. For quadcopters, this translates to higher payload capacity and improved hover efficiency. However, larger propellers also demand more torque from the motors, which can strain the battery and reduce flight time. Conversely, smaller diameters allow for faster RPM changes, enhancing agility and responsiveness during sharp maneuvers.

We must strike a balance: a diameter too small may starve the quadcopter of lift, while one too large risks overwhelming the motors and destabilizing the craft.

In our project we have selected a propeller having a diameter of 17 inches, which is compatible with our selected BLDC motor for producing required torque.

Pitch Distribution: Pitch refers to the angle at which the propeller blade slices through the air. Unlike a fixed-pitch propeller, modern quadcopter blades often feature a variable pitch distribution along their span.

Near the hub, the pitch is steeper to generate strong initial thrust, while it gradually flattens toward the tips to minimize drag-induced turbulence. This design ensures that the inner sections of the blade work harder at lower RPMs, while the outer sections operate efficiently at higher speeds.

For quadcopters, this optimization allows motors to maintain steady RPMs during hover while enabling rapid acceleration during directional changes.

An improperly pitched blade can cause motor overheating, erratic flight behavior, and excessive noise.

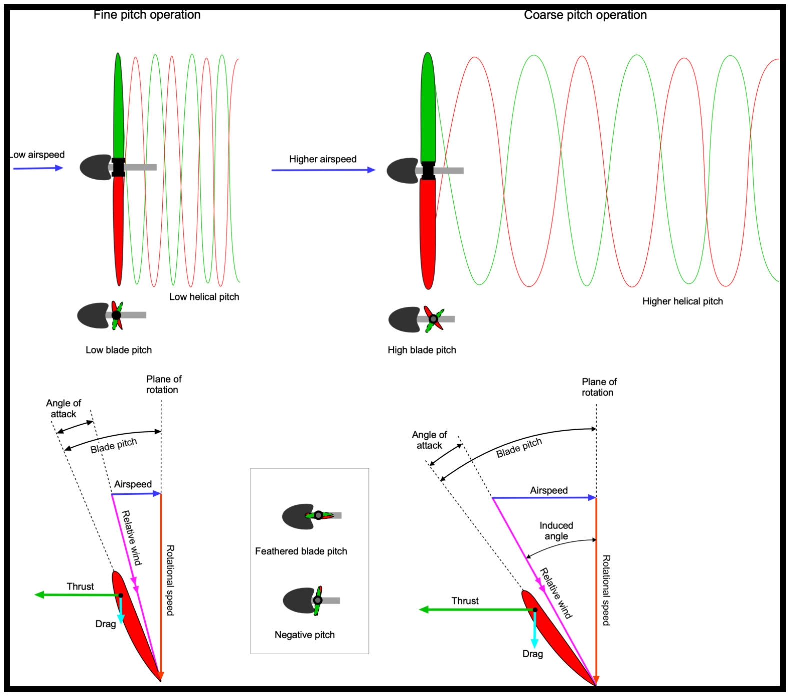


Fig.:- Effect of propeller design on its pitch

Blade Twist: A deliberate twist in the propeller blade, where the angle of attack decreases from the root to the tip. This geometric feature is critical for quadcopters operating in dynamic conditions, such as forward flight or windy environments.

At high speeds, the tips of untwisted blades can stall due to excessive angle of attack, creating turbulent vortices that reduce efficiency and destabilize the craft. Washout (blade twist) mitigates this by reducing the tip's angle of attack, ensuring smooth airflow across the entire blade. For quadcopters, this translates to smoother transitions between hover and forward flight, reduced vibration, and enhanced stability during aggressive maneuvers.

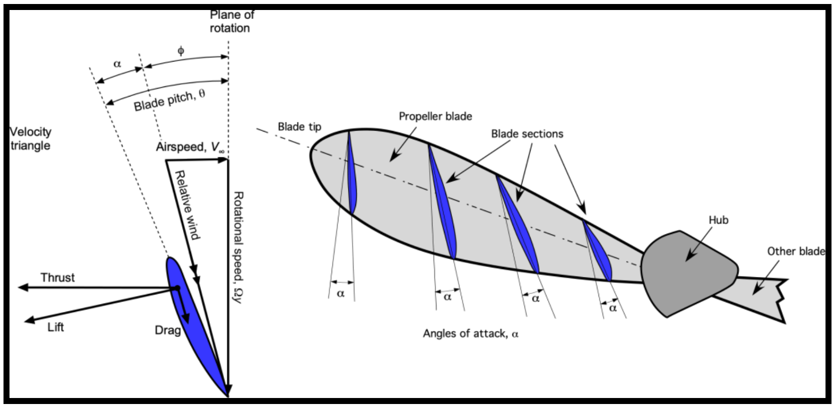


Fig.:- Blade twist in a propeller

Camber and Thickness: The cross-sectional shape of a propeller blade, its airfoil, is defined by camber (curvature) and thickness. A highly cambered airfoil generates more lift at a given angle of attack, which is advantageous for slow-speed hover. However, excessive camber increases drag, forcing motors to work harder and draining battery life.

Thickness, meanwhile, affects structural integrity and aerodynamic efficiency. Thicker blades are more durable and resistant to bending, but create additional drag. Thinner blades slice through the air cleanly but may flex under load, altering their pitch and reducing performance.

For quadcopters, the ideal airfoil balances camber and thickness to maximize lift-to-drag ratio, ensuring efficient energy use without compromising durability.

Propeller setup in a quadcopter:-

Reference:- Propeller setup

The quadcopter uses counter rotating propellers. The orientation and spinning direction of the motors are dependent on the flight controller.

The common setup and the two types of propellers, a clockwise rotating propeller and a counter clockwise propeller.

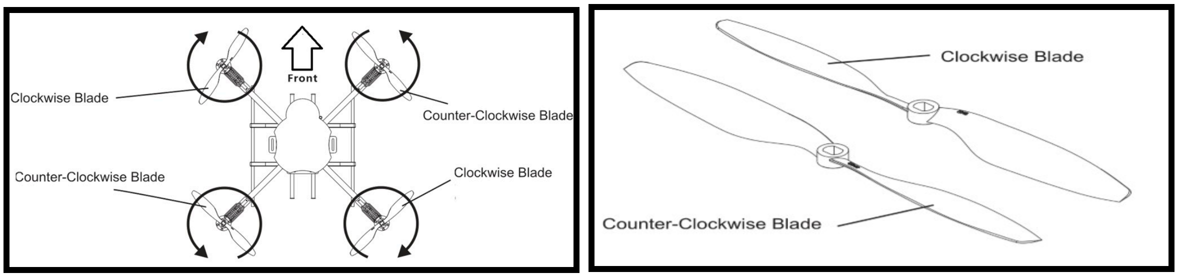


Fig.:- Propeller setup in a quadcopter and its type based on direction of rotation

Stall condition in a propeller:-

Reference:- [Stall condition]

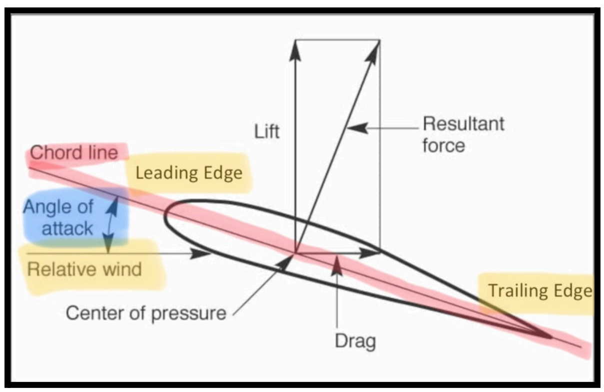


Fig.:- Propeller design parameters and resultant force (thrust)

What is a stall?

A stall condition occurs when a propeller blade's angle of attack (the angle between the blade's chord line and the incoming airflow) becomes too steep, causing airflow to separate from the blade surface. This disrupts lift generation and increases drag, leading to a sudden loss of thrust, vibrations and instability—critical issues for quadcopters.

Recovery from Stall:-

If exceeding the critical angle of attack is what caused the stall, immediately decrease the AOA to regain the smooth airflow over the wings. Simultaneously, one will need to add power to avoid bleeding off any more airspeed. Lower the nose to the horizon by using slight and calm, yet responsive inputs on the elevator controls.

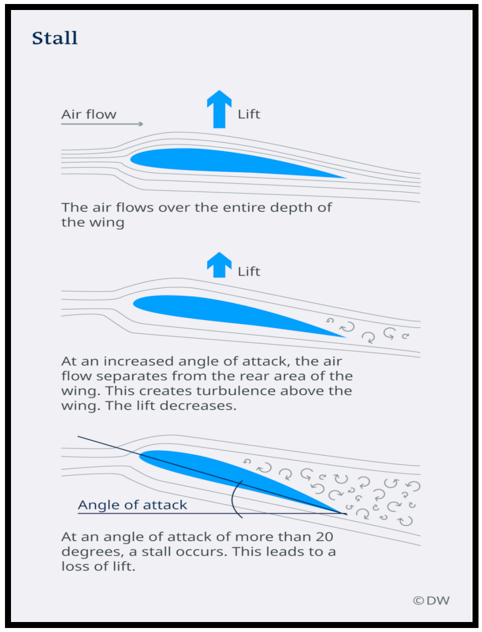


Fig.:- Stall condition in a propeller

Selected Propeller:- [Reflex Drive RD 1760 17-inch Folding Propeller with Hub – CW]

Optimum propeller separation distance and effect:

Reference:- [Design Condition for propellers]

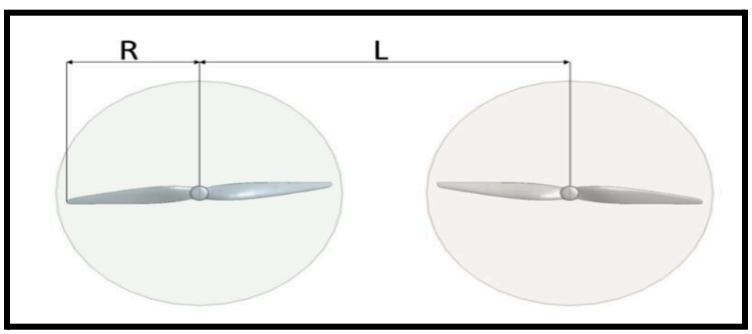


Fig.:- Sketch of two propellers with their relevant Land R parameters.

The study investigates the influence of propeller separation distances and airflow conditions on multi-rotor UAV performance through numerical simulations.

To determine the influence of propeller separation distance on the performance of the propellers in different flow conditions, the figure of merit (FM), power coefficient (C_P), and wake visualization were employed as key parameters.

Two configurations were analyzed:-

1. **A dual-propeller setup** (spaced perpendicular to onset flow). The dual-propeller tests examined four separation distances (L/R = 2.2, 2.8, 3.6, 5.2) under three flow conditions:
    - Still air
    - 5 m/s laminar flow
    - 5 m/s turbulent flow (15% turbulence intensity).
2. **A quadcopter**. The quadcopter, spaced at the optimal (L/R = 2.8), was tested under the same conditions.

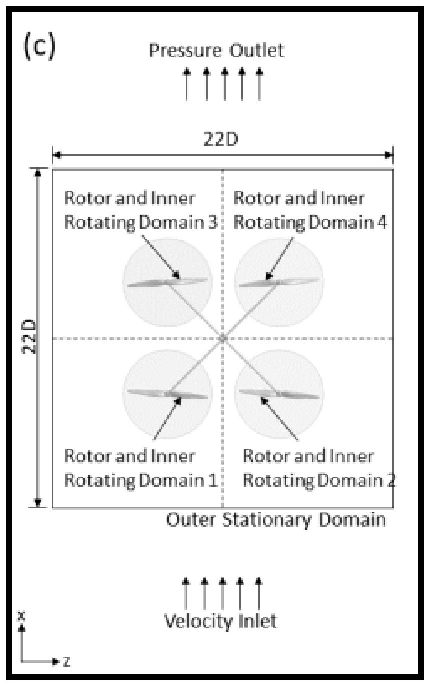


Fig.:- Quadcopter setup for the simulation study (D refers to the diameter of the propeller)

Results for quadcopter:-

- The L/R = 2.8 propeller separation was found to be optimal for quadcopter setup as smaller separations would be unconventional when compared to commercially available quadrotors.
- For each of the three different flow conditions, the FM (Figure of merit) and C_P values were measured for the front and back propeller pairs, as well as the entire quadcopter which are depicted below:-

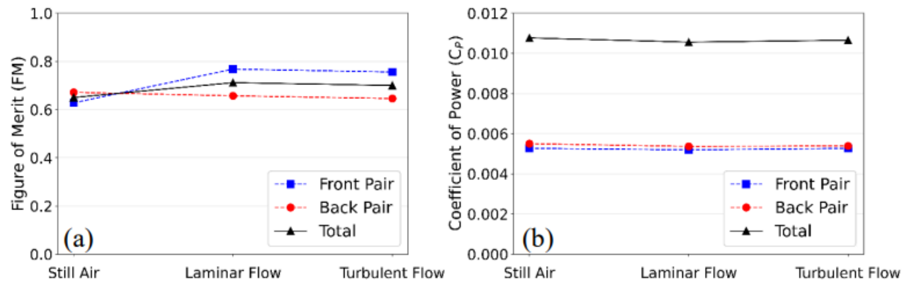


Fig. 9 (a) Figure of merit and (b) coefficient of power for the front two, back two, and all four propellers of the quadcopter. Results for still air, 5 m/s nonturbulent, and 5 m/s turbulent conditions are all shown.

Fig.:- FM and C_P values for 3 cases studied for quadcopter setup

- In both cases of onset flow, the front propeller pair shows a higher FM compared to the back propeller pair. On average, the FM decreases by 14.5% from the front to the back propeller pair across the two onset flow cases. This decrease is most likely due to the interaction between propeller wakes, where the wake of the front propeller is swept downstream into the wake of the back propeller.
- This indicates that only the back propellers are adversely affected by the wake interaction, which can be visualised using a velocity contour taken from the side view of the quadcopter as shown below.

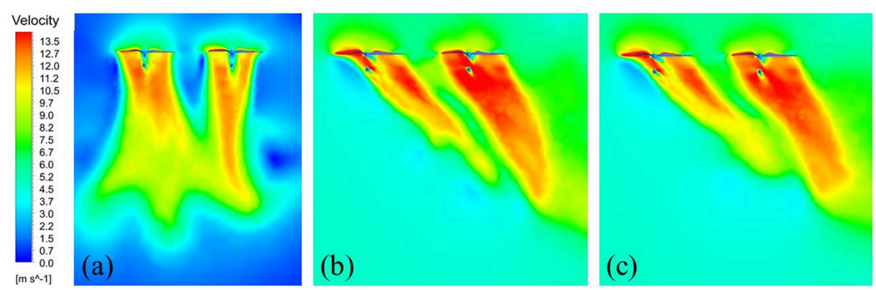


Fig. 10 Velocity contour of the quadrotor setup for the flow conditions of (a) still air, (b) 5 m/s laminar onset flow and (c) 5 m/s onset flow with 15% turbulence intensity.

Fig.:- Velocity contour results for the quadcopter setup

- In Fig. 10(a) (refer above figure), it can be observed that there is minimal mixing of the front and back propeller wakes during the still air simulation. The velocity contours for the 5 m/s onset flow cases can be seen in Fig. 10(b) and Fig. 10(c), and these show an increase in near-field wake interaction relative to the still air case.

- The FM plot and velocity contours for the moving air of the quadcopter setup indicates the presence of wake interactions for the high washout propellers spaced parallel to the onset flow direction, resulting in a drop in performance for downwind propellers.

Conclusion:-

1. Perpendicular propeller separation had a negligible impact on efficiency, with a mere 2.2% variation in the figure of merit across all cases. However, propeller washout (blade twist) strongly influenced optimal spacing.
2. In the quadcopter setup, downstream propellers aligned parallel to the onset flow suffered a 14.5% efficiency drop due to turbulence from upstream propellers.
3. This highlights that optimizing parallel separation is critical for high-washout propellers, while perpendicular spacing is less consequential.
4. These findings simplify UAV design by prioritizing airflow-aligned propeller placement over total spacing.

Relation with our project:-

We have chosen a propeller of diameter d= 17 inches.

So the *optimal distance* between the two consecutive propellers would be:-

L= 2.8 × 17/2 = **23.8 inches**.

Length of *outer stationary domain* (taken as square) = 22D (from simulation)

= 22×17 = **374 inches**.

Dynamics of Propeller and Thrust Generation:

A propeller, whether on a fixed-wing aircraft or a multirotor drone, generates thrust by accelerating air. Its blades are airfoils designed to create a pressure difference between their upper and lower surfaces. This results in the movement of air through the propeller disc—either pushing air backwards for aircraft (producing forward motion), or pushing air downwards for drones (generating upward lift or thrust for hovering and climbing).

Momentum theory

References:- Static propeller momentum theory
Propeller-static-dynamic-thrust-equation

Thrust can be defined using Newton's Second Law, which in its general form is:

$T=d/dt(mv)$,

If we assume constant velocity, the thrust for a stationary (static) propeller becomes:

$T=d/dt(m) \cdot V_e$

Where:

> $d/dt(m)$= mass flow rate through the propeller,
> V_e = velocity of the air exiting the propeller.

For a moving aircraft or drone (dynamic case), we account for the fact that the incoming air already has velocity V_o, so only the change in momentum contributes to thrust:

$T=d/dt(m) \cdot (V_e-V_o)$

Now, expressing the mass flow rate in terms of air properties and the propeller area:

$d/dt(m)=\rho \cdot V_p \cdot A=\rho \cdot V_p \cdot \pi r^2$

V_p : air velocity at the propeller (V□)

Substituting this back:

$T = \rho \cdot V_p \cdot \pi r^2 \cdot (V_e - V_o)$

Since V_p is difficult to measure directly, an alternative form based on pressure differential across the propeller disc is used:

$T = \Delta p \cdot A$, with change in pressure , $\Delta p = ½ \cdot \rho \cdot (V_e^2 - V_o^2)$

$T = ½ \cdot \rho \cdot \pi r^2 \cdot (V_e^2 - V_o^2)$

This equation provides a theoretical estimation of thrust using fluid momentum and pressure changes across the propeller disc.

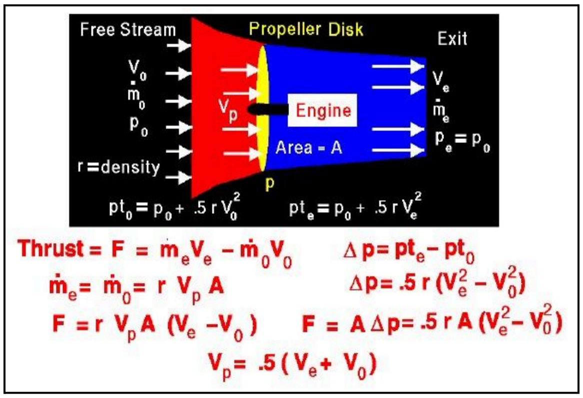


Fig.:- Static Propeller Thrust Equation(from nasa.gov)

Blade Element Theory (BET) Thrust Equation

References:- BET , NPTEL reference for BET

While the previous formulation uses bulk flow analysis, Blade Element Theory (BET) provides a more granular approach by analyzing aerodynamic forces on differential blade elements.

The total thrust from BET (after integrating across all blade elements and using airfoil lift theory) results in an equation of the form:

$T = C_Q \times \rho \times A \times \omega^2 \times R^2$

Where:

T = total thrust
C_Q= thrust coefficient (depends on blade geometry and pitch)
ρ = air density
$A=\pi R^2$ = propeller disc area
ω= angular velocity (rad/s)
R = propeller radius

This BET-based thrust model assumes quasi-steady aerodynamics and incorporates blade characteristics such as chord length, pitch angle, and number of blades into $C_{T.}$

Maneuvering of the air taxi:-

To maneuver an air taxi, such as a quadcopter-style electric vertical takeoff and landing (eVTOL) vehicle, in various directions (forward, backward, left, right) and to rotate about its vertical axis (yaw), we rely on the principles of multirotor dynamics. These maneuvers are achieved by adjusting the speeds of individual rotors, thereby controlling the vehicle's orientation and position in three-dimensional space.

Axes of Movement and Corresponding Controls

A quadcopter operates with six degrees of freedom: three translational (movement along axes) and three rotational (rotation about axes):

Translational Movements:
Forward/Backward (Pitch): Tilting the vehicle forward or backward.
Left/Right (Roll): Tilting the vehicle sideways to the left or right.
Up/Down (Throttle): Ascending or descending vertically.

Rotational Movements:
Yaw (Rotation about Vertical Axis): Rotating the vehicle left or right around its vertical axis.
Pitch (Rotation about Lateral Axis): Tilting the vehicle forward or backward around its side-to-side axis.
Roll (Rotation about Longitudinal Axis): Tilting the vehicle left or right around its front-to-back axis.

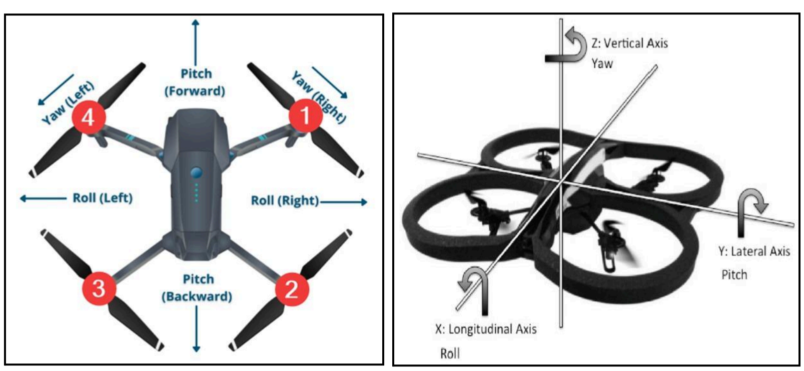


Fig.:- Translational and Rotational movements for a quadcopter

Control Mechanisms for Each Movement

1. *Pitch* (Forward/Backward Movement):-

   Mechanism: Adjust the speed of the front and rear rotors.
   Action: Use rotor speed changes to induce torque about the pitch axis (Y-axis):

   τ_{pitch}(torque)= $l \cdot k_T \cdot (\omega_3^2+\omega_2^2-\omega_1^2-\omega_4^2)$,

   where l is the distance from the center of mass (CoM) of the quadcopter to each motor (rotor)

   To pitch forward: Increase ω_3,ω_2, or decrease ω_1,ω_4
   To pitch backward: Increase ω_1,ω_4, or decrease ω_3,ω_2

   Resulting Horizontal Thrust

   After the drone pitches by angle θ, the vertical thrust vector is tilted. The forward force is:

   $F_{forward} = T \cdot \sin(\theta)$

   Where:

   $T = k_T(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2)$,

   where ;

   k_T: Empirically measured thrust coefficient (varies by propeller and motor combo)

   θ: Pitch angle (measured by IMU in real drones)
   So:

   $F_{forward} = k_T(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2) \cdot \sin(\theta)$

   Forward Acceleration:

   $a_x = F_{forward}/m = k_T(\omega_1^2+\omega_2^2+\omega_3^2+\omega_4^2) \cdot \sin(\theta)/m$*

*Empirically, this equation has been validated in real flight tests (see Mahony et al., 2012; Pounds et al., 2010).

2. *Roll* (Left/Right Movement):
   Mechanism: Adjust the speed of the left and right rotors.
   Action: To move right, increase the speed of the left rotors and decrease the speed of the right rotors, causing the vehicle to tilt right. The opposite applies to the left movement.
3. *Yaw* (Rotation about Vertical Axis):
   Mechanism: Exploit the torque differences between clockwise (CW) and counterclockwise (CCW) rotating rotors.
   Action: To rotate right (clockwise), increase the speed of the CCW rotors and decrease the speed of the CW rotors. The opposite applies for left (counter-clockwise) rotation.
4. *Pitch* (Rotation about Lateral Axis):
   Mechanism: Adjust the speed of the front and back rotors to create a torque around the lateral (side-to-side) axis.
   Action: To pitch forward, increase the speed of the rear rotors and decrease the speed of the front rotors.
   To pitch backward, do the opposite—increase the front rotors and decrease the rear rotors.
5. *Roll* (Rotation about Longitudinal Axis):
   Mechanism: Adjust the speed of the left and right rotors to create a torque around the longitudinal (front-to-back) axis.
   Action: To roll right, increase the speed of the left rotors and decrease the speed of the right rotors.
   To roll left, increase the right rotors and decrease the left rotors.

Reference: **Tufts Self-Serve Blogs and Websites**

Estimation of the Flight Time of eVTOL:-

The flight time of an electric vertical take-off and landing (eVTOL) aircraft is primarily governed by the energy stored in the battery and the rate at which the system consumes that energy. The energy consumption is determined by the electrical power drawn by all propulsion units, which in turn depends on the mechanical load, motor efficiency, and supply voltage.

To estimate flight time, we relate the battery's capacity (in ampere-hours, Ah) to the total current draw (in amperes, A) of the system:

Flight Time = Battery Capacity(Ah) ×60/Total Current Draw

For example ;

Battery Capacity = **8000mAh** (Chosen battery capacity for our project)

Current drawn = **197.02 A**

So *Flight Time* = 8 × 60/197.02 = **2.436 min**

To increase flight time we can use Battery with higher capacity , for a battery with 16000mAh capacity (Bonka 22.2V 16000mAh 25C 6S Li-Po Battery)

Flight Time = 16 × 60/197.02 = **4.872 min**

This formula assumes continuous operation at a steady power level. However, real-life conditions—such as throttle variation, aerodynamic disturbances, and safety margins—reduce the effective flight time. Typically, only 80–85% of the nominal battery capacity is usable to preserve battery health and prevent voltage drops during high current draws.

Reference: **Flight time calculation**

Power Inverter to drive Motor:

A power inverter is a critical component in an eVTOL system used to convert DC power from the battery into three-phase AC power required by BLDC motors. It performs this conversion using high-frequency switching devices (like MOSFETs or IGBTs) controlled by pulse-width modulation (PWM) techniques—commonly sinusoidal PWM for smoother torque and efficiency. The inverter must match the motor's voltage and current requirements while maintaining fast dynamic response and thermal reliability. Efficient inverter design directly impacts propulsion performance, system stability, and overall energy efficiency.

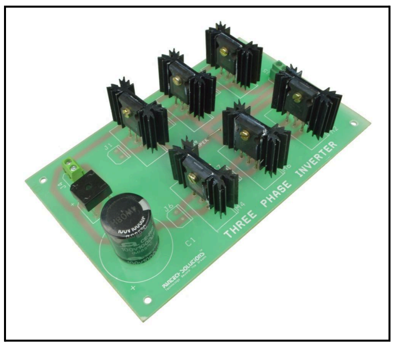


Fig : three Phase Power inverter

Sine Pwm Switching Scheme:

Sinusoidal PWM (SPWM) for a three-phase inverter involves comparing three 120° phase shifted sine waves (modulating signals) with a high-frequency triangular carrier wave to generate gate pulses. This results in variable-width pulses that control the inverter switches, producing a near-sinusoidal AC output.

Space Vector Pulse Width Modulation:
Space Vector PWM (SVPWM) is a technique for generating PWM signals to control 3 phase inverters with maximum voltage utilization. It models the 3-phase voltages as a single rotating vector in a 2D plane and selects the nearest switching vectors to approximate it. Compared to sine PWM, SVPWM reduces harmonic distortion and increases output voltage by ~15%.

Motor Control Fundamentals

Flying electric vehicles (air taxis) require motors that are not only lightweight and efficient but also capable of rapid and precise response. Achieving this performance hinges on effective control of both motor speed and torque.

Speed Control:
Controlling motor speed involves regulating the rotational velocity of the rotor. Since the speed of AC motors is directly related to the frequency of the input supply, inverters or variable frequency drives (VFDs) are used to modulate this frequency. This enables smooth acceleration, deceleration, and steady operation—crucial for critical maneuvers such as take-off, hovering, and landing.

Torque Control:
Torque control adjusts the motor's rotational force by regulating voltage or current. Advanced methods like Field-Oriented Control (FOC) and Direct Torque Control (DTC) enable precise, independent control. FOC splits current into torque and flux components, while DTC directly manipulates them via real-time voltage vector selection. Both offer high responsiveness and efficiency, critical for stable flight.

Integration of Speed and Torque Control

In advanced high-speed motor systems used in flying electric vehicles, speed and torque control are seamlessly integrated within a unified control framework to achieve optimal responsiveness, stability, and efficiency.

Components:
Speed is regulated using controllers such as PI or PID, which adjust reference commands to maintain the desired motor speed. Simultaneously, torque is managed through algorithms like Vector Control or Direct Torque Control, ensuring real-time regulation of motor output.

Working Mechanism:
The speed controller generates a torque reference based on the difference between desired and actual speed. This reference is then used by the torque controller to precisely control current and voltage supplied to the motor, ensuring immediate torque delivery.

PRACTICAL CALCULATIONS

Parameter Calculation for Components of eVTOL (Air Taxi).

1. eVTOL basic design requirements:-
    a. Required payload (P) = 5 kg
    b. Expected weight of eVTOL (w) = 10 kg
    c. Net weight to be lifted off the ground (W) = P + w = 15 kg
    d. As we will be making eVTOL similar to a quadcopter, we will be using 4 BLDC motors (Reflex Drive RD 5008 KV370 Motor 6S)

    SPECIFICATION:

    i. Motor Type – Outrunner
    ii. KV Rating – 370 KV (RPM/volts)
    iii. Maximum Thrust – 4.2 KG
    iv. Stator Poles / Magnet Poles – 24 / 28
    v. No load current – 1.5A
    vi. Motor Efficiency – 90.99%
    vii. Weight (Including Cable) – 135 grams
    viii. Voltage Range – 4S-6S
    ix. Maximum Current (15 Sec) – 51A
    x. Maximum Power (15 Sec) – 1224W
    xi. Motor Dimensions – 55.6mm x 27mm
    xii. Motor Torque Constant (N.m/A) – 0.029415
    xiii. Cable Type / Length – 15 AWG / 180mm
    xiv. Copper wire Temperature Rating – 90 ℃
    xv. Winding material – 100% Copper
    xvi. IP Rating – IP34
    xvii. Maximum Operating Temperature – 150 ℃
    xviii. Recommended Propeller – 17*60 (Folding)

    e. With each BLDC motor, we will attach 1 propeller (Reflex Drive RD 1760 17-inch Folding Propeller with Hub – CW)

    SPECIFICATION:

    i. Diameter: 17 inches
    ii. Pitch: 6.0 inches

iii. Weight: 40 Grams
iv. Material: Polycarbonate
v. One Propeller With Aluminium Hub

2. Speed of the motor for the specified voltage source:-
    a. We will be using a 6S LiPo battery in our eVOLT as the primary voltage source (Pro-Range 22.2V 8000mAh 25C 6S Lithium Polymer Battery Pack)

    SPECIFICATION:

    i. Model No: Pro-Range 8000/6S-25C
    ii. Capacity: 8000 mAh
    iii. Output Voltage: 22.2 V
    iv. Discharge Current: 25C
    v. Charge Rate: 1~3 C
    vi. Max. Continuous Discharge: 25C (200 A)
    vii. Max. Burst Discharge: 50C (400 A)
    viii. Max. Charge Rate: 5C
    ix. Weight: 1125 g
    x. Dimensions: 18 x 5 x 6 cm
    xi. Balance Plug: JST-XH
    xii. Discharge Plug: HXT 4mm

    b. *Maximum speed of the motor* = KV rating of the motor * Maximum Potential (fully charged battery) = 370 × 25.2 = **9324 RPM** #reference
    c. *Nominal speed of the motor* = KV rating of the motor * Nominal Potential (continuous operation of battery) = 370 × 22.2 = **8214 RPM**
    d. Based on our requirements, we can run our motor within the **8214 - 9324 RPM range**. We can control the motor speed by controlling the applied voltage using the **PWM technique**.
3. Thrust Required At Motor:-
    a. For vertical hovering, the Total thrust generated by the 4 propellers must equal the total weight of the vehicle (including payload, frame, battery, motors, electronics, etc).
    b. Therefore, *Total Thrust* (**T**) = Net Weight to be lifted off the ground * g = W * g = 15 × 9.81= **147.15 N**
    c. We are using 4 propellers in our eVTOL, so the *thrust generated by each propeller* would be (**$T_{per\ propeller}$**) = T/4 = **36.7875 N**

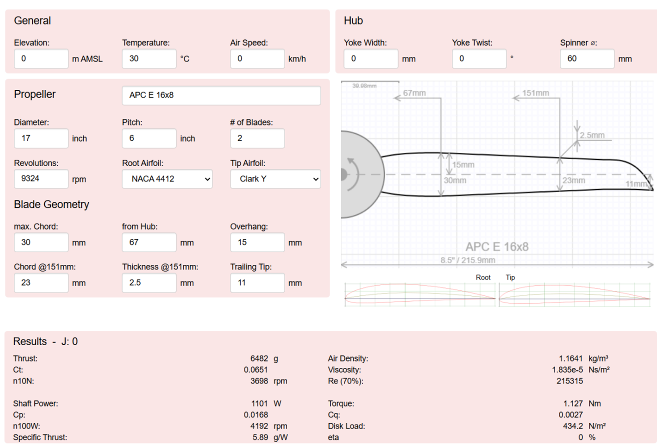
d. We will ensure that each propeller generates **1.5 times** the required thrust, considering **thrust reserve** for maneuvers, gusts, and redundancy.

e. Therefore, *Net Thrust per propeller* (**T_{net}**) = 1.5 × $T_{\text{per propeller}}$ = **55.18125 N = 5.627 kg-force**

4. Propeller Thrust, Torque, and Shaft Power practical calculations based on its dimensions using the [eCalc website]:-

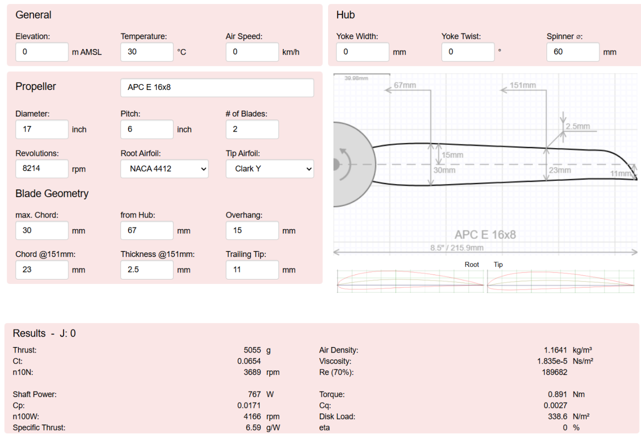
a. *Maximum Values* (@maximum motor speed):-

- ω_{max} = **9324 RPM**
- *Maximum Thrust* = **6.482 kg-force**
- *Maximum Torque* = **1.127 N-m**
- *Maximum Shaft Power* = **1101 W**



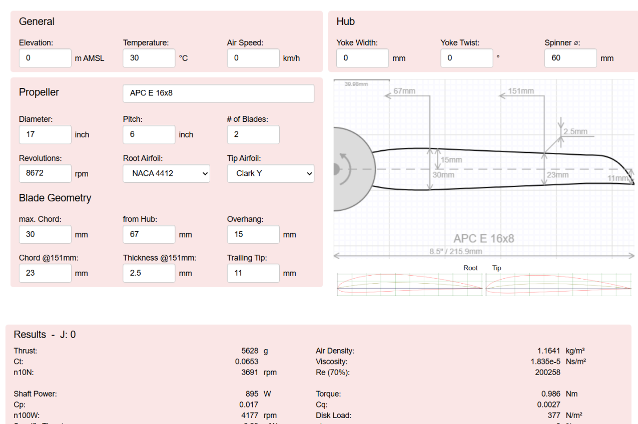
b. *Nominal Values* (@Nominal motor speed):-

- ω_{nom} = **8214 RPM**
- *Nominal Thrust* = **5.055 kg-force**
- *Nominal Torque* = **0.891 N-m**
- *Nominal Shaft Power* = **767 w**



c. *Required Values* (for specified payload):-

- ω_{req} = **8672 RPM**
- *Thrust Produced* = **5.628 kg-force**
- *Torque Produced* = **0.986 N-m**
- *Shaft Power Produced* = **895 W**



d. **CONCLUSION:-** The parameter values obtained under ideal conditions using ***eCalc*** satisfy our design requirements, while also incorporating appropriate **safety margins** to account for practical variations such as changes in temperature, elevation, and airspeed. *This ensures the system's performance remains reliable and robust under practical operating conditions.*

e. We will be using $\boldsymbol{\omega_{req}}$ slightly greater than the actual value (say **8800 RPM**) for further calculations, considering practical scenarios.

5. Thrust, Torque, and Power calculations using theoretical equations:-

a. The relationship between propeller thrust T and rotational speed ω is given by:-

$$T = C_T \times \rho \times \omega^2 \times D^4$$ #Reference

Where:

- T = Thrust per propeller (N)
- C_T = Thrust coefficient ≈ 0.0653 (for specified propeller running at ω = 8800 RPM)
- ρ = Air density (1.225 kg/m³ at sea level)
- ω = Propeller rotational speed (revolutions per second) = 146.66
- D = Diameter of specified propeller = 17 inch = 0.4318 m

➢ Therefore, *Thrust Produced* (T) = **59.814 N** = **6.099 kg-force**

➢ The calculated thrust per propeller exceeds the *Required Net Thrust* (T_{net}) of **55.18125 N**, ensuring sufficient thrust margin to meet our performance requirements and accommodate real-life variations & operational conditions.

b. The relationship between torque required at the shaft τ and rotational speed ω is given by:-

$$\tau = C_q \times \rho \times \omega^2 \times D^5$$

Where:

- τ = Torque required at the shaft of each motor (N-m)
- C_q = Torque coefficient ≈ 0.0027 (for specified propeller running at ω = 8800 RPM)
- ρ = Air density (1.225 kg/m³ at sea level)
- ω = Propeller rotational speed (revolutions per second) = 146.66
- D = Diameter of specified propeller = 17 inch = 0.4318 m

➢ Therefore, *Torque Required* per propeller (τ) = **1.0679 N-m**

➢ *Net Torque Required* (τ_{net}) = 4 * τ = **4.2716 N-m**

c. *Mechanical Power* (P_{mech}) needed at each motor = Torque * Rotational Speed #reference

∴ $\mathbf{P_{mech}}$ = τ × ω = **984.119 W**

Hence, *Net Mechanical Power* ($P_{net\ mech}$) needed = 4 * P_{mech} = **3936.476 W**

6. Calculations for Current Drawn and Power Supplied to the Motor using Battery/Supply (P_{elec}):-

   a. *Electrical Power* needed by each motor (P_{elec}) = P_{mech} ÷ (Motor Efficiency)

      P_{elec} = 984.119 and Motor Efficiency = 90% = 0.9

      ∴ **P_{elec} = 1093.466 W**

      Hence, *Net Electrical Power* ($P_{net\ elec}$) needed = 4 * P_{elec} = **4373.862 W**

   b. *Current drawn* by each motor from the DC source:

      $P_{DC\ side} = P_{AC\ side}$ (considering no loss in inverter)

      $I_{DC} \times V_{DC} = P_{elec}$

      $I_{DC} = P_{elec}/V_{DC} = 1093.466/22.2$

      ∴ **I_{DC} = 49.255 A** (Average current drawn by each motor from battery)

      Hence, *Net Current Drawn* from the supply (I_{net}) = **197.02 A**

   c. These values, thus obtained, are all under safety limits for motor and battery.

FUTURE WORK :

- Conduct detailed simulations of the eVTOL system using suitable software to validate calculated parameters such as thrust, torque, and current drawn.
- Account for real-world factors like aerodynamic turbulence to improve the accuracy of practical performance predictions.
- Evaluate how closely the simulation results align with theoretical values and refine the design accordingly.
- Upon achieving satisfactory simulation results, proceed to the hardware implementation phase.
- Study and implement advanced navigation and control systems to enable:
    - Obstacle avoidance (e.g., trees, buildings)
    - GPS-based autonomous waypoint tracking
    - Reliable communication between onboard receivers and ground transmitters to avoid signal loss during flight.

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