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Design & Performance Evaluation of 3- Blade Propeller for Multi-Rotor UAV

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Abstract— **This work emphasis on research, designing and development of an 3-blade efficient propeller for an existing UAV to produce maximum thrust in an operating range of 2000 rpm to 3000 rpm. And CFD analysis will be performed to determine the performance characteristics of the propeller.**

Keywords—UAV, Quadcopter, Propellers, Multirotors, VTOL

I. INTRODUCTION

A propeller is a device that converts mechanical energy into a force, which we call thrust, and is used to propel the vehicle to which it is attached. The propeller features one or more lifting surfaces called propeller blades1 that are rotated rapidly using an engine. The thrust is the aerodynamic lift force produced by the blades and is identical to the force produced by a wing. Propellers are, by far, the most common means of generating thrust for any general Aviation aircrafts or modern UAVs.

II. 3-BLADE PROPELLER GEOMETRY

A.

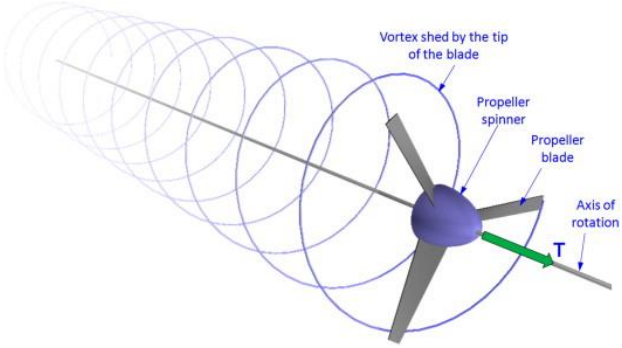


Figure 1 – Propeller Helix

A three-bladed propeller is shown in Figure 1, rotating about an axis. The spinner is an aerodynamically shaped cover, whose purpose is to reduce the drag of the hub of the propeller and to protect it from the elements. The propeller blades are what generate the thrust of the device, denoted by T. The pressure differential between the front and aft face of the propeller blade results in a vortex that is shed from the tip of the blade and is carried back by the airflow going through the propeller. This forms the typical helical shape shown in the figure-1. A frontal projection of the three-bladed propeller is shown below.

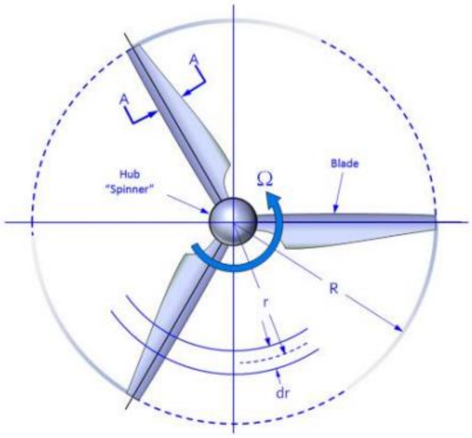


Figure-2 Frontal projection of the 3-blade propeller

Where R is the blade radius, r is the radius to an arbitrary blade station, and U is the rotation rate, typically in radians per second or minutes. The blade of a propeller is really a cantilevered wing that moves in a circular path rather than along a straight one. Just like an airplane's wing, the plan form of the propeller blade has a profound impact on the magnitude of the thrust force created, as well as at what "cost." What constitutes "cost" is the amount of power required to rotate it, as well as side effects such as noise.

III. GEOMETRIC PROPELLER PITCH

Consider the propeller in **Figure - 3**, whose diameter is D and radius is R. As the propeller rotates through a full circle, its tip rotates through an arc length (circumference) of C = 3.14xD = 2x3.14xR. As the propeller rotates it "screws" itself forward a certain distance P for each full rotation. The distance it would cover in one full revolution is called the geometric pitch or pitch distance, PD, of the propeller. It is commonly specified in terms of inches of pitch. Thus a propeller designated as a 42-inch pitch prop would move 42 inches forward in one revolution (using the metal screw through wood analogy). The angle the helix makes to the rotation plane is called the geometric pitch angle and is denoted by β.

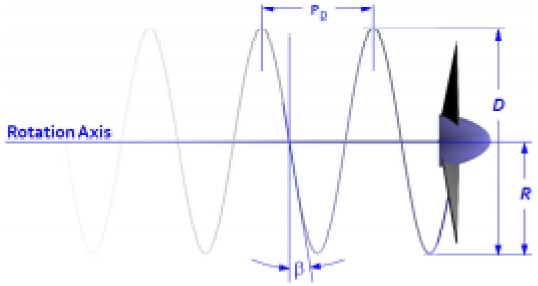


Figure-3 schematic showing propeller properties

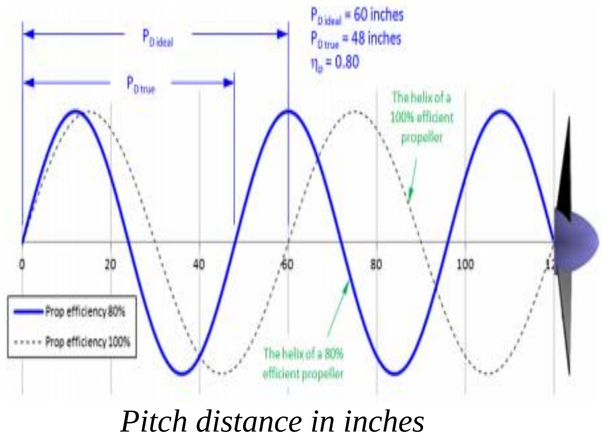


Figure-4 the propeller will advance a shorter distance (pitch distance) in a low-viscosity fluid than the geometric pitch indicates

IV. FUNDAMENTAL FORMULATION

Considering the geometry shown in figure-3 we can now define the following characteristics of the propeller:

$$\tan\beta = \frac{P_D}{2\pi\, r_{ref}} \qquad \text{(Eq. 1)}$$

Where;

r_{ref} = reference radius, usually 75% of the propeller radius R

PD = Pitch distance of the propeller

Generally, the value of PD ranges from 60% to 85% of the diameter of the propeller. The pitch-to-diameter ratio is also used to identify propellers

Pitch-to-diameter ratio

$$\frac{P_D}{D} \qquad \text{(Eq. 2)}$$

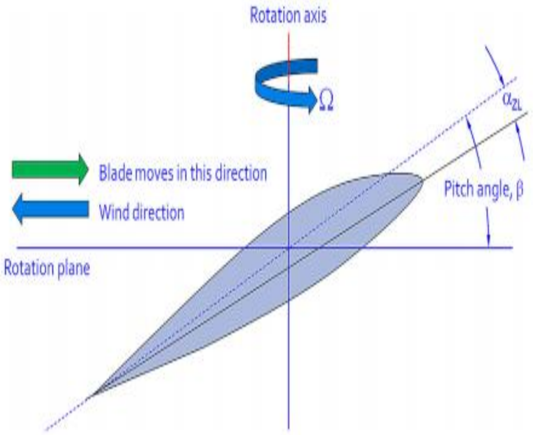


Figure-5 Definition of propeller pitch angle

A propeller moving through a low-viscosity fluid like air will cover less distance per revolution than the geometric pitch would indicate. Therefore, the angle formed between the rotation plane and a tangent to the blade tip helix at each blade station is less than the geometric pitch angle. This angle is called the helix angle and is denoted by ϕ. It can be estimated if the forward speed of the propeller is known using the following expression:

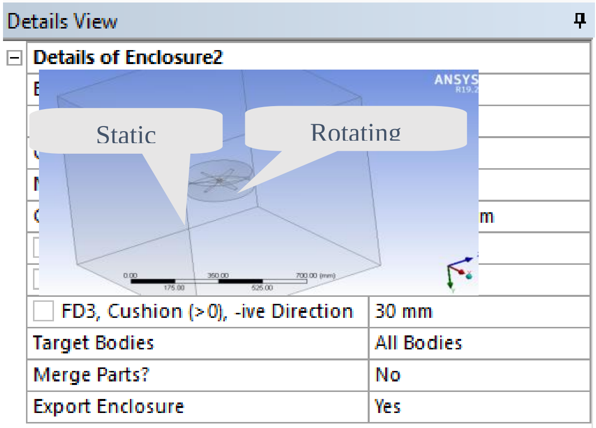
Helix angle:

$$\tan\phi = \frac{2\pi r n}{v_o} \qquad \text{(Eq. 3)}$$

V. DESIGN STATEMENT

Propellers for UAVs operate under various operating conditions, ranging from the sea level to stratosphere altitudes. Apparently, it is appropriate to adopt a variable pitch system to provide the optimal propulsive efficiency under the aforementioned conditions. However, its adoption imposes additional weight and complexity due to the addition of actuators and pitch links. Additionally, these pitch links and actuators will practically be exposed to external flows at low temperatures from −70 to −80° C at stratospheric altitudes. The extreme environment and mechanical complexity may lead to an increased possibility of malfunctions and uncertainty. Consequently, the demand for reliability and being ultra-lightweight, which are top-level constraints of UAVs, makes it difficult to adopt the variable pitch system. Therefore, fixed-pitch propellers are generally used. When the fixed-pitch propellers are optimized for aerodynamic performance at high-altitude operation, the required torque, approximately at sea level, becomes considerably large and exceeds the specification for electric motors. This can lead to low climbing performances or, sometimes, the inability to climb. On the other hand, as altitude increases, the rotational speed of the propeller gradually increments, which consequently results in an increase of the required power. Thus, the maximum required power occurs under high-altitude climbing conditions. In this respect, the design of UAV propellers must not only take into account the two conflicting constraints but also simultaneously maximize efficiency under the desired operating condition.

VI. DESIGN REQUIREMENTS



Details View

Details of Enclosure2

☐ FD3, Cushion (>0), -ive Direction	30 mm
Target Bodies	All Bodies
Merge Parts?	No
Export Enclosure	Yes

The ultralight weight aircraft, has a total length, total width and design total weight of approximately 1.2 m, .5 m, and 2.5 kg, respectively. It uses 4-propellers mounted on each arm. The maximum available torque should correspond to the climb condition at sea level, requiring the highest thrust. The maximum power condition should correspond to the climb operation where the highest rotational speed is required. Considering the motor diameter, the design propeller diameter was fixed at 0.25 m. as a geometry constraint. In conformance with the mission profile, which is mainly aimed at climbing to high altitudes, the climb condition of 4 km was set as the propeller design point.

VII. AIRFOIL SELECTION & POSITIONING[1]

Airfoil	r/R	Chord length in inches C	R	Chord length in mm C	Pitch in inches	Pitch in mm	Alpha
NACA 4515	0.3	1.5915	38.1	40.4241	0.7968	20.23872	4.8
NACA 5513	0.4	1.875	50.8	47.625	1.1512	29.24048	5.199
NACA 5513	0.5	2.109	63.5	53.5686	1.5485	39.3319	5.59
NACA 4512	0.6	2.285	76.2	58.039	1.9557	49.67478	5.92
NACA 4510	0.7	2.393	88.9	60.7822	2.3338	59.27852	6.05
NACA 4410	0.8	2.351	101.6	59.7154	2.6948	68.44792	6.11
NACA 4309	0.9	2.0985	114.3	53.3019	3.00465	76.31811	6.05
NACA 4309	1	1.2565	127	31.9151	3.203	81.3562	5.82

VIII. CAD MODEL PREPARATION

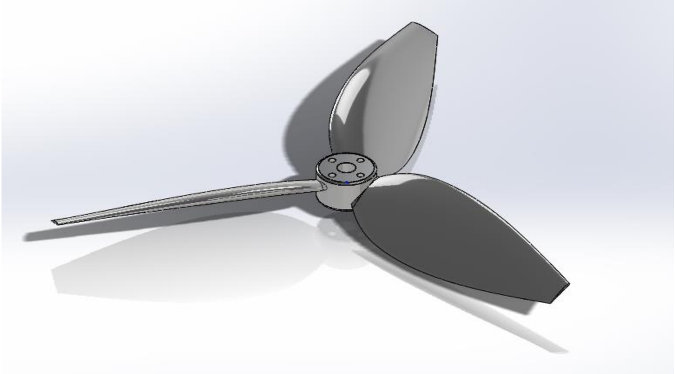


Figure-7 10 inch Propeller cad model

IX. CFD ANALYSIS PREPARATION

Considerations

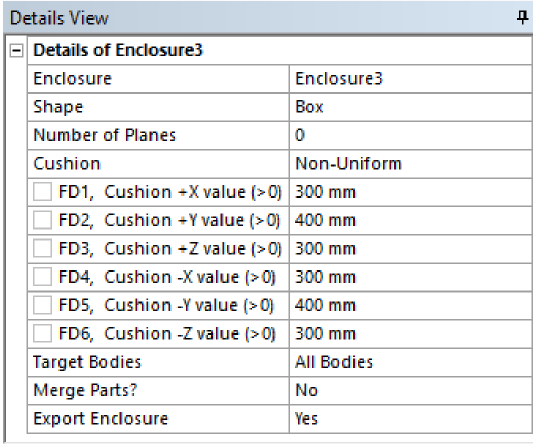
Speed – 3000 rpm
Inlet Velocity – 15m/s
Angle of attack = 10°
Propeller Dia = 250 mm
Number of Blades = 3
Propeller Material = Carbon fiber

Step-1

Creating Enclosures – Cylindrical Enclosures

Step – 2

Creating Enclosures – Box Enclosure



Details View

Details of Enclosure3

Enclosure	Enclosure3
Shape	Box
Number of Planes	0
Cushion	Non-Uniform
☐ FD1, Cushion +X value (>0)	300 mm
☐ FD2, Cushion +Y value (>0)	400 mm
☐ FD3, Cushion +Z value (>0)	300 mm
☐ FD4, Cushion -X value (>0)	300 mm
☐ FD5, Cushion -Y value (>0)	400 mm
☐ FD6, Cushion -Z value (>0)	300 mm
Target Bodies	All Bodies
Merge Parts?	No
Export Enclosure	Yes

Step -3

Creating Boolean-1
Tool Body: Propeller
Target Body: Cylindrical Enclosure
Now we have only 2 Bodies i.e.

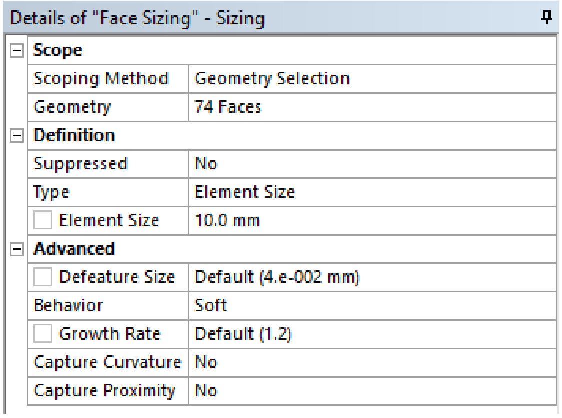
1. Rotating Domain
2. Static Domain

Creating Boolean-2
Tool Body: Rotating Domain
Target Body: Static Domain

Step-4

A. Meshing

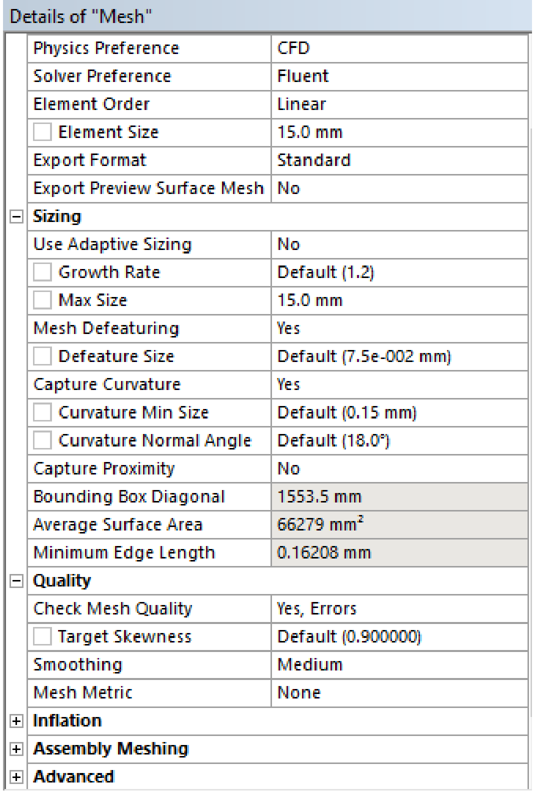
1. Inserted Mesh sizing for rotating domain
   Max- Element size – 8 mm



Details of "Face Sizing" - Sizing

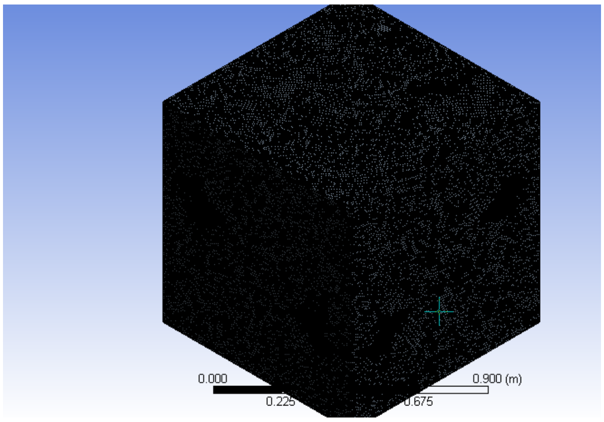
Scope	
Scoping Method	Geometry Selection
Geometry	74 Faces
Definition	
Suppressed	No
Type	Element Size
☐ Element Size	10.0 mm
Advanced	
☐ Defeature Size	Default (4.e-002 mm)
Behavior	Soft
☐ Growth Rate	Default (1.2)
Capture Curvature	No
Capture Proximity	No

2. Mesh Settings – Static Domain
Max- Element Size – 15 mm



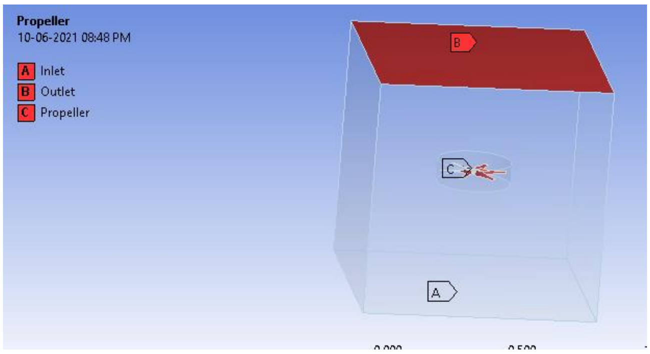
Details of "Mesh"

Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
☐ Element Size	15.0 mm
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	No
☐ Growth Rate	Default (1.2)
☐ Max Size	15.0 mm
Mesh Defeaturing	Yes
☐ Defeature Size	Default (7.5e-002 mm)
Capture Curvature	Yes
☐ Curvature Min Size	Default (0.15 mm)
☐ Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	1553.5 mm
Average Surface Area	66279 mm²
Minimum Edge Length	0.16208 mm
Quality	
Check Mesh Quality	Yes, Errors
☐ Target Skewness	Default (0.900000)
Smoothing	Medium
Mesh Metric	None
Inflation	
Assembly Meshing	
Advanced	



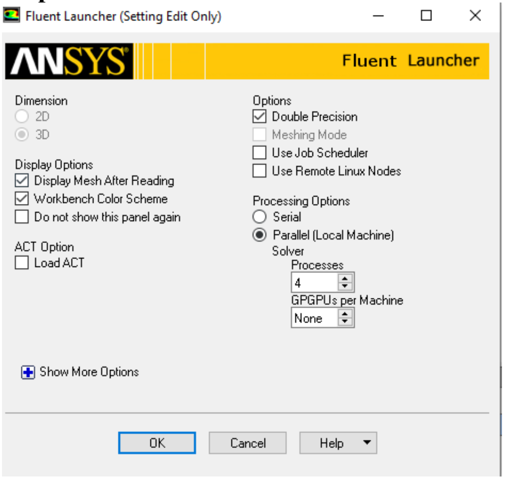
Step-5

Creating named Selections
Propeller
Inlet
Outlet



Step-6
Updating the Mesh

Step-7



Dimension
○ 2D
● 3D

Options
☑ Double Precision
☐ Meshing Mode
☐ Use Job Scheduler
☐ Use Remote Linux Nodes

Display Options
☑ Display Mesh After Reading
☑ Workbench Color Scheme
☐ Do not show this panel again

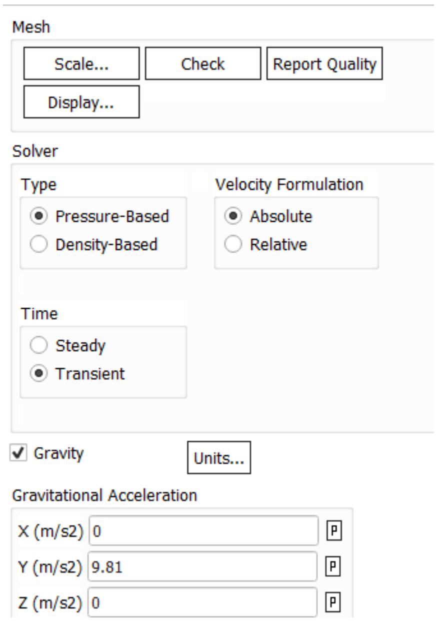
ACT Option
☐ Load ACT

Processing Options
○ Serial
● Parallel (Local Machine)
Solver
Processes: 4
GPGPUs per Machine: None

Show More Options

Step-8

Setup
Selecting Transient and Gravity



Mesh

Scale... Check Report Quality
Display...

Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

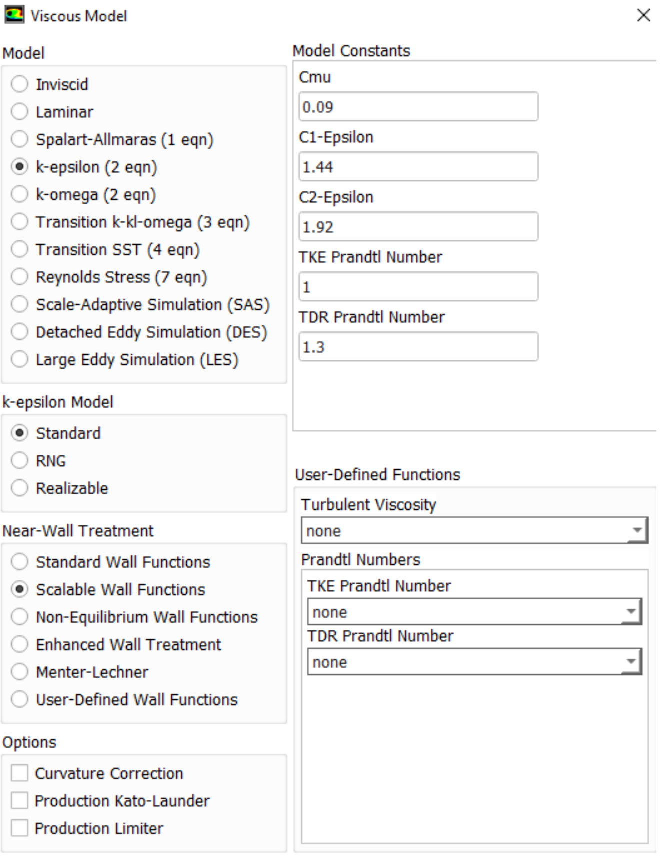
Time
○ Steady
● Transient

☑ Gravity Units...

Gravitational Acceleration
X (m/s2) 0
Y (m/s2) 9.81
Z (m/s2) 0

Step-9

Model – Viscous Laminar



Viscous Model

Model
○ Inviscid
○ Laminar
○ Spalart-Allmaras (1 eqn)
● k-epsilon (2 eqn)
○ k-omega (2 eqn)
○ Transition k-kl-omega (3 eqn)
○ Transition SST (4 eqn)
○ Reynolds Stress (7 eqn)
○ Scale-Adaptive Simulation (SAS)
○ Detached Eddy Simulation (DES)
○ Large Eddy Simulation (LES)

k-epsilon Model
● Standard
○ RNG
○ Realizable

Near-Wall Treatment
○ Standard Wall Functions
● Scalable Wall Functions
○ Non-Equilibrium Wall Functions
○ Enhanced Wall Treatment
○ Menter-Lechner
○ User-Defined Wall Functions

Options
☐ Curvature Correction
☐ Production Kato-Launder
☐ Production Limiter

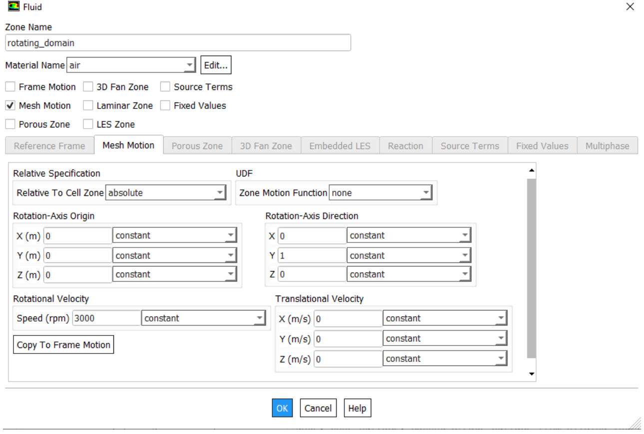
Model Constants
Cmu 0.09
C1-Epsilon 1.44
C2-Epsilon 1.92
TKE Prandtl Number 1
TDR Prandtl Number 1.3

User-Defined Functions
Turbulent Viscosity none
Prandtl Numbers
TKE Prandtl Number none
TDR Prandtl Number none

Step-10

Cell Zone Conditions

Rotating Domain



Fluid

Zone Name rotating_domain
Material Name air Edit...

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

Reference Frame | Mesh Motion | Porous Zone | 3D Fan Zone | Embedded LES | Reaction | Source Terms | Fixed Values | Multiphase

Relative Specification
Relative To Cell Zone absolute

UDF
Zone Motion Function none

Rotation-Axis Origin
X (m) 0 constant
Y (m) 0 constant
Z (m) 0 constant

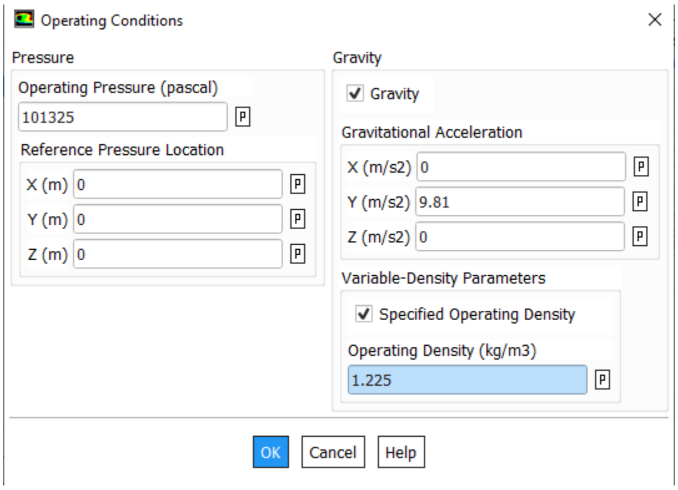
Rotation-Axis Direction
X 0 constant
Y 1 constant
Z 0 constant

Rotational Velocity
Speed (rpm) 3000 constant
Copy To Frame Motion

Translational Velocity
X (m/s) 0 constant
Y (m/s) 0 constant
Z (m/s) 0 constant

OK Cancel Help

Static Domain



Operating Conditions

Pressure
Operating Pressure (pascal) 101325
Reference Pressure Location
X (m) 0
Y (m) 0
Z (m) 0

Gravity
☑ Gravity
Gravitational Acceleration
X (m/s2) 0
Y (m/s2) 9.81
Z (m/s2) 0

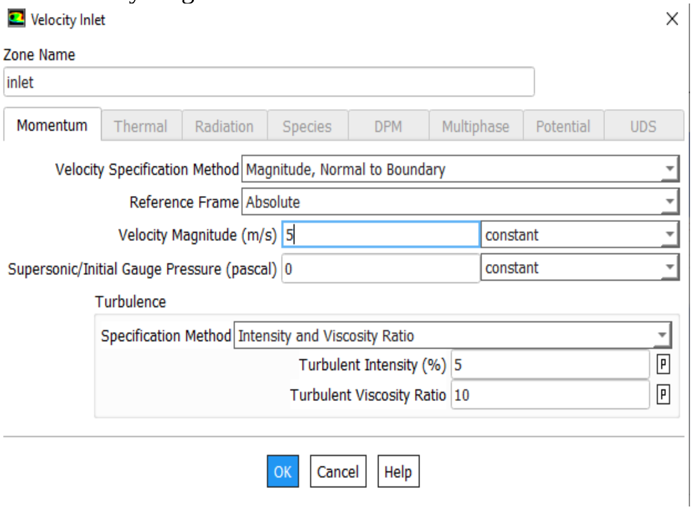
Variable-Density Parameters
☑ Specified Operating Density
Operating Density (kg/m3) 1.225

OK Cancel Help

Step-11

Boundary Conditions

Inlet velocity magnitude = 5 m/s



Velocity Inlet

Zone Name inlet

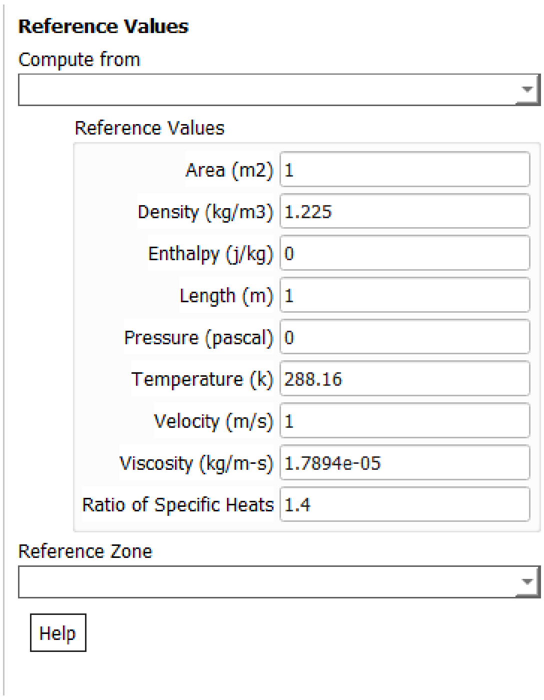
Momentum | Thermal | Radiation | Species | DPM | Multiphase | Potential | UDS

Velocity Specification Method Magnitude, Normal to Boundary
Reference Frame Absolute
Velocity Magnitude (m/s) 5 constant
Supersonic/Initial Gauge Pressure (pascal) 0 constant

Turbulence
Specification Method Intensity and Viscosity Ratio
Turbulent Intensity (%) 5
Turbulent Viscosity Ratio 10

OK Cancel Help

Reference Values



Reference Values

Compute from

Reference Values

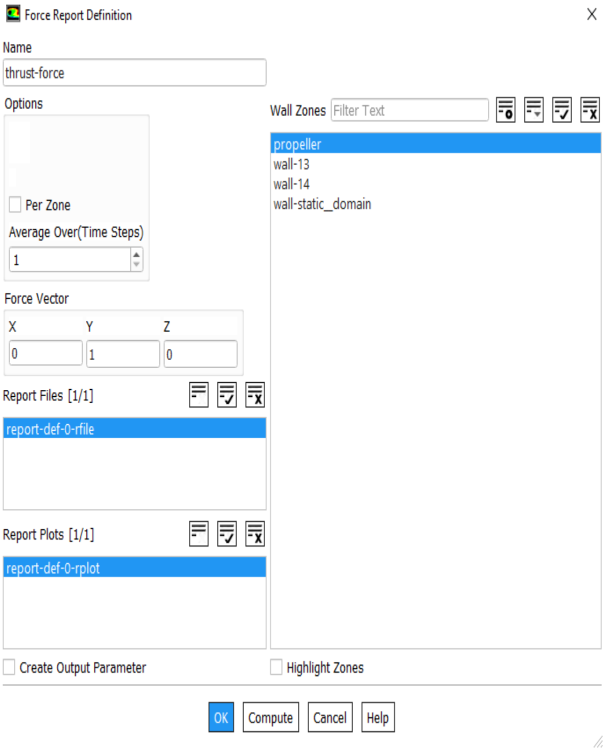
Area (m2) 1
Density (kg/m3) 1.225
Enthalpy (j/kg) 0
Length (m) 1
Pressure (pascal) 0
Temperature (k) 288.16
Velocity (m/s) 1
Viscosity (kg/m-s) 1.7894e-05
Ratio of Specific Heats 1.4

Reference Zone

Step-12

Report Definitions

Create new force report- Thrust Force



Force Report Definition

Name: thrust-force

Options

☐ Per Zone

Average Over(Time Steps): 1

Force Vector

X: 0
Y: 1
Z: 0

Report Files [1/1]: report-def-0-rfile

Report Plots [1/1]: report-def-0-rplot

Wall Zones: propeller (selected), wall-13, wall-14, wall-static_domain

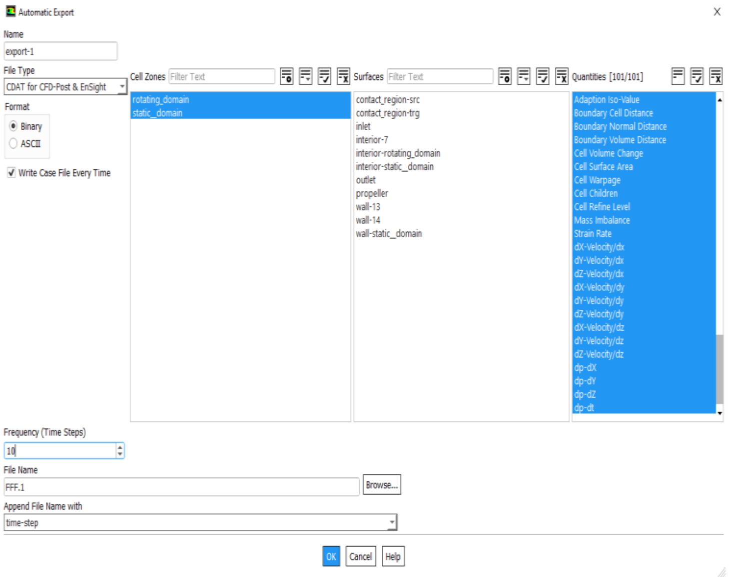
☐ Create Output Parameter

☐ Highlight Zones

B. *Step-13*

C. *Calculation Activities*

Create- Solution Data Export



Automatic Export

Name: export-1

File Type: CDAT for CFD-Post & EnSight

Format: ● Binary ○ ASCII

☑ Write Case File Every Time

Cell Zones: rotating_domain, static_domain (selected)

Surfaces: contact_region-src, contact_region-trg, inlet, interior-7, interior-rotating_domain, interior-static_domain, outlet, propeller, wall-13, wall-14, wall-static_domain

Quantities [101/101]: Adaption Iso-Value, Boundary Cell Distance, Boundary Normal Distance, Boundary Volume Distance, Cell Volume Change, Cell Surface Area, Cell Warpage, Cell Children, Cell Refine Level, Mass Imbalance, Strain Rate, dX-Velocity/dx, dY-Velocity/dx, dZ-Velocity/dx, dX-Velocity/dy, dY-Velocity/dy, dZ-Velocity/dy, dX-Velocity/dz, dY-Velocity/dz, dZ-Velocity/dz, dp-dX, dp-dY, dp-dZ, dp-dt

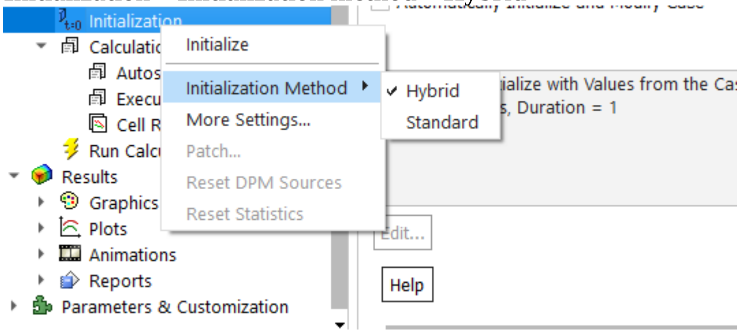
Frequency (Time Steps): 10

File Name: FFF.1

Append File Name with: time-step

Step-14

Initialization – Initialization method – Hybrid



Step-15

Initialize

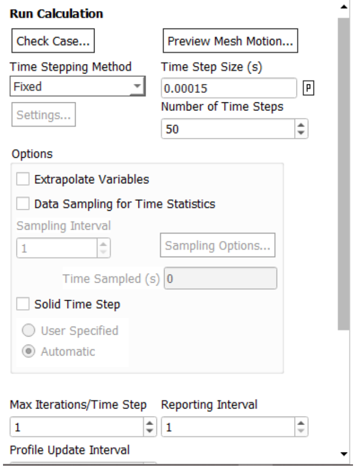
Step-16

Run Calculation

Time Steps – 0.00015

Number of Steps – 10

Max. Iterations / step – 1 (selected for less computing time)



Run Calculation

Time Stepping Method: Fixed

Time Step Size (s): 0.00015

Number of Time Steps: 50

Options

☐ Extrapolate Variables

☐ Data Sampling for Time Statistics

Sampling Interval: 1

Time Sampled (s): 0

☐ Solid Time Step

○ User Specified

● Automatic

Max Iterations/Time Step: 1

Reporting Interval: 1

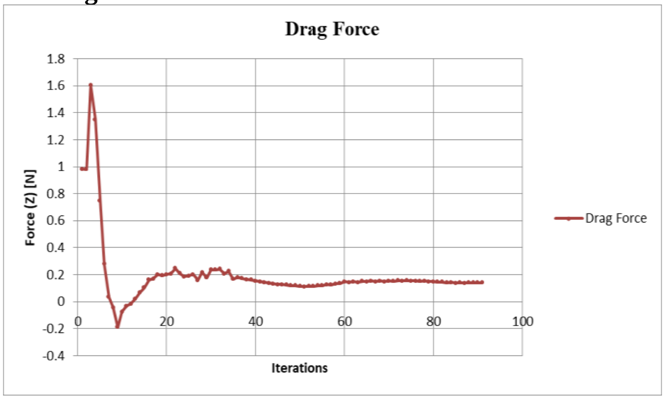
Profile Update Interval

Step- 17

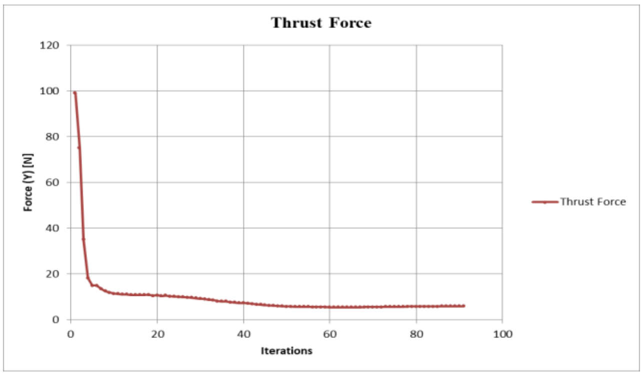
Run Calculation

X. RESULTS

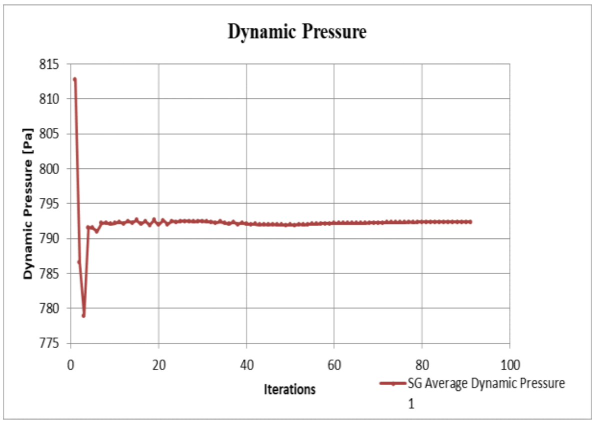
Drag Force



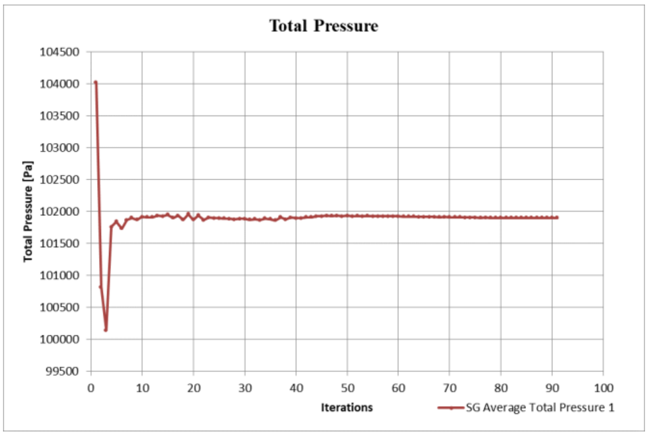
Thrust Force



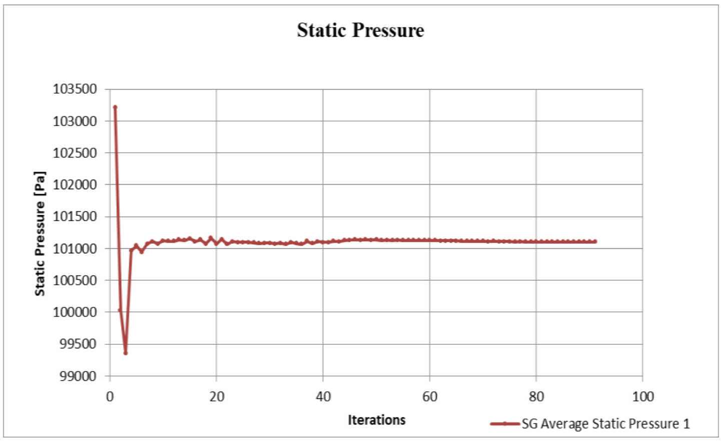
Dynamic Pressure



Total pressure

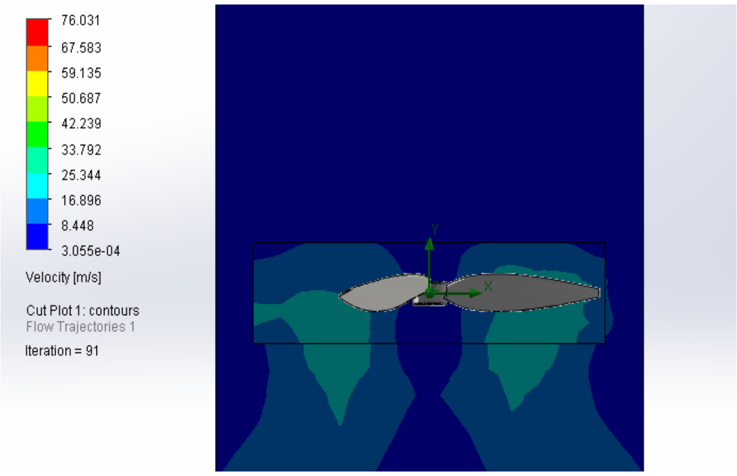


Static Pressure

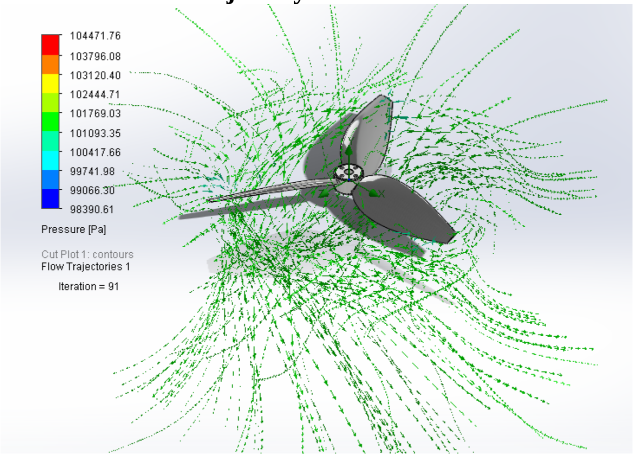


Counter plots

Velocity contour



Pressure Flow trajectory



XI. CONCLUSION

A 3 blade propeller of diameter 254mm and a 3D CAD model is prepared with the combination of airfoils and radial distribution of NACA 4309, NACA 4410, NACA 4510, NACA 4512, NACA 5513 & NACA 5521 is prepared. The model is been analyzed through Ansys CFD following the steps as discussed above. It's been found that the developed propeller with carbon fiber material is capable of producing 5.7 N of thrust force at 3000 rpm. Hence we can use the developed propeller in any mini UAVs with the 1200 KV motor with an 11.1 v Lipo battery.

XII. REFERENCES

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