AERO DESIGN CHALLENGE 2021

FABRICATION REPORT

ADC20210136 – THE SKYTROOPERS

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DATE: 7th February 2021

Statement of Compliance

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1. LITERATURE REVIEW

To understand the design procedure of a propeller different scholarly articles on propeller design theories were reviewed.

W.J. Rankine et al. [1] stated the Momentum Conservation theory; it provides a method to analyse propeller flow characteristics considering that the propeller causes changes in kinetic energy, momentum and static pressure. But this method was designed with highly ideal conditions (uniform disk loading, infinite blade etc.) and neglecting all 3D- effects.

Again in 1878, William Froude [2] designed another theory which involves breaking the blade down into smaller parts then determining the forces on each of these small elements. These forces are then integrated along the blade elements over one revolution. This theory is known as the 'Blade element Theory'. But this method lacked the ability to model the induced inflow velocity on the propeller disk and neglected some 3-D effects.

As an improvement Sydney Goldstein [3], gave how a propeller blade can be considered as a bound vortex system to analyse propeller's aerodynamic characteristics. This is mainly based on the foundations laid by the Kutta-Joukowski Condition. This theory uses the Lifting Line approximation as a basis as given in. Hospodář Pavel et al.[4] compared, LLT and BET on the basis of the output provided; LLT is considered more suitable for geometry optimisation and BET allows for a parametric study based optimisation.

A improved theory based on the above theories which tries to eliminate the errors to design an optimum propeller was stated by Adkins & Liebeck [5]. The theory comprises of improved equations and elimination of the approximations prevalent in the classical design theory. An iterative scheme was introduced for the accurate calculation of vortex displacement velocity and flow angle distributions.

For manufacturing process of the propeller methods like VARTM, Pultrusion and 3-D Printing were taken into consideration.

A detailed description of the VARTM (Vacuum Assisted Resin Transfer Moulding) process is given in [6]. The materials and resins that can be used in the process are also discussed. H Syamsudin et al. [7] gave an in depth comparison between Hand Lay-up and VART Moulding process. Further comparison and trade-offs are explained on page 9.

2. DESIGN APPROACH

For the design of the propeller to be more purpose-specific, conventional propeller designing methods were analyzed along with the designing methods discussed in the SAE webinar sessions. The overall approach is explained further on.

3. ENVIRONMENTAL CONDITIONS

For the designing of the propeller standard environmental conditions were considered.

Serial No.	Parameter	Value
1	Density	1.2210 Kg/m^3
2	Kinematic Viscosity	0.000014607 m^2/s
3	Speed of Sound	340.29 m/s

Table 1: Environmental Conditions

4. DESIGN THEORIES AND SOFTWARE

Serial No.	Title	Blade Element Method	Lifting Line Method
1	Pre-requisites	Propeller geometry and no. of blades	Geometry and circulation distribution
2	Limitations	Interference between propeller blades is not considered	Does not take into account compressible flow, viscous flow.
3	Accuracy	Higher	Lower

Table 2: Comparison between BET & LLT

The team shortlisted BET and lifting line method and eliminated momentum theory as it is applicable only in ideal conditions. Table 2 shows the comparison between the theories.

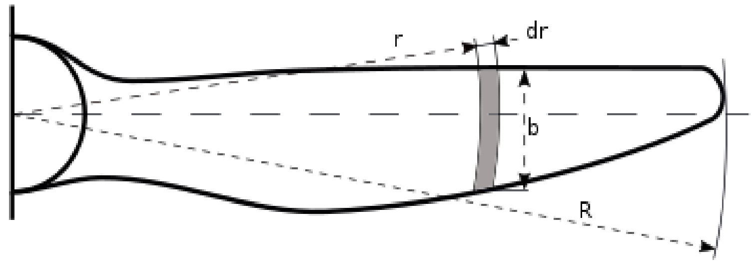

Figure 1: Division of Blade in BET

Figure 1 explains how the propeller is blade is divided into sections along the radius in BET in the designing process. But as the errors in BET are resolved by the improved theory by Adkins & Liebeck [6], the team decided to select the improved theory over the BET. Our team used Javaprop based on this improved theory as the primary designing software for the propeller.

JavaProp is a simple program based on the theory by Adkins & Liebeck [6]. It is divided into four sections; Design, Airfoils, Geometry, Analysis and Options. First, inputs such as airfoil type, diameter, RPM etc. need to be provided. On designing the theoretical propeller efficiency, blade angle, thrust,

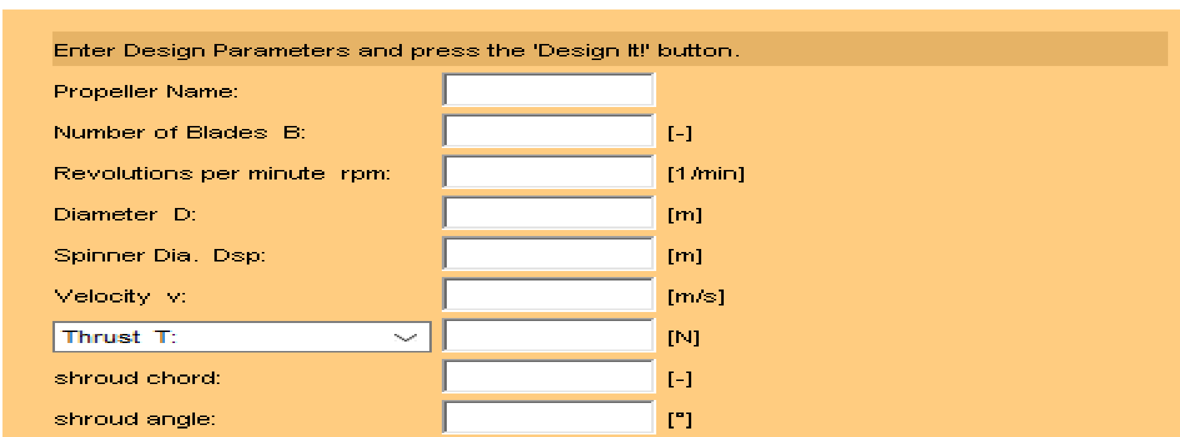

Figure 2: Javaprop Inputs

speed, torque and power are obtained. The overall blade geometry is determined from the results from the geometry section. Results are presented under "Multi Analysis" subsection. The team analyzed from static to the full operating range.

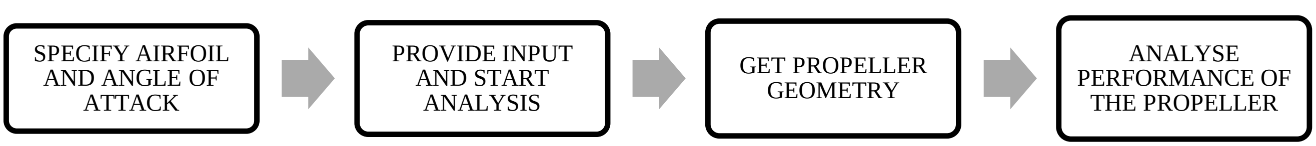

Figure 3: Javaprop Designing Process

5. METHODOLOGY

Initially, the team decided to create models by iterating for diameter values with a fixed RPM but as the designing progressed, we found out that for a specific propeller to give its maximum performance output, the RPM needs to be iterated as well.

The team had to go through an iterative process to fulfil the requirements. Javaprop provides 3 input options as the basic requirement a propeller has to achieve, from which thrust was selected as the input parameter. The take-off velocity (before rotation) and required thrust were calculated by equations 1&2. The specific operating conditions are given in table 3.

$$V_{TO} = \left(\frac{2W}{\rho S Cl_{max}}\right)^{0.5} * 1.1$$

Equation 3: Take-Off Velocity

$$T_R = \left\{\frac{mV_{TO}^2}{2S_{TO}} + D + \mu(W - L)\right\}$$

Equation 4: Thrust Required

Serial No.	Parameter	Value
1	Take-off Velocity before Rotation	11.68 m/s
2	Thrust	28.857 N

Table 3: Operating Condition

Propellers were created using javaprop by defining constraints on diameter and rpm as follows:

10 ≤ Diameter ≤ 20 Inch; 1000 ≤ RPM ≤ 5000

Hub Diameter was fixed at 1.25 Inches which was bare minimum value of diameter required for manufacturing and structural purposes.

6. PROPELLER DESIGN

6.1. Airfoil Selection

The Cl-Cd curves of some selected airfoils were analyzed and MH-114 airfoil was selected for the propeller on the basis of following points:

a. High Cl/Cd value at 3° angle of attack, which is the optimum angle of attack for a blade airfoil.

b. Low Cd values for reducing torque leading to higher efficiency and lower power requirements.

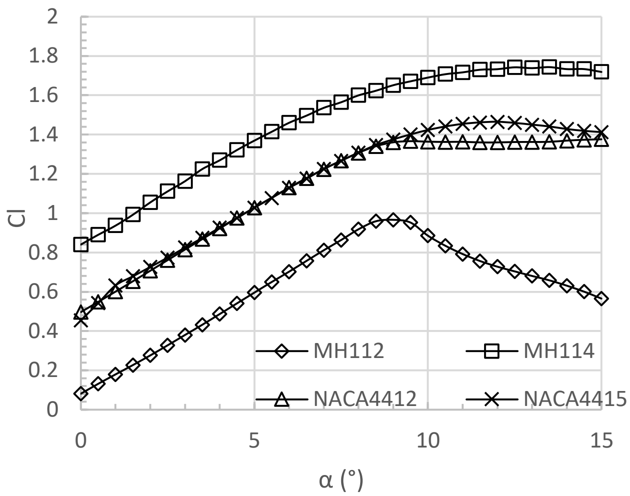

Figure 4: Cl vs α

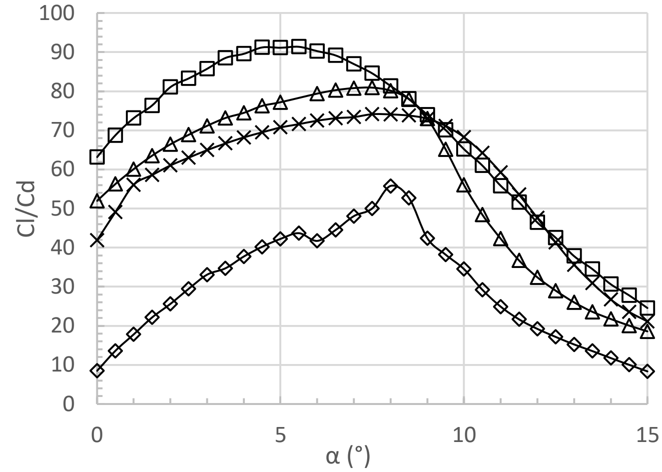

Figure 5: Cl/Cd vs α

6.2. Number of Blades

Serial No.	Parameter	Two Bladed Propeller	Three Bladed Propeller
1	Thrust	Comparatively Lower	Higher
2	Torque	lower	Higher
3	Efficiency	Higher	Lower
4	Weight	Less	More

Table 4: Propeller Configuration Trade-Off

Considering the high power consumption due to higher torque requirement of three bladed propeller and as the two bladed propeller satisfied the thrust requirement, the team chose a two bladed propeller.

6.3. Analysis of Propeller Models

As mentioned in the methodology, the team iterated for the diameter and rpm values. Figure: 6 shows the step-by-step process carried out by the team. Javaprop was unable to create propellers with diameters as low as 10 inches due to unrealistic values of thrust loading.

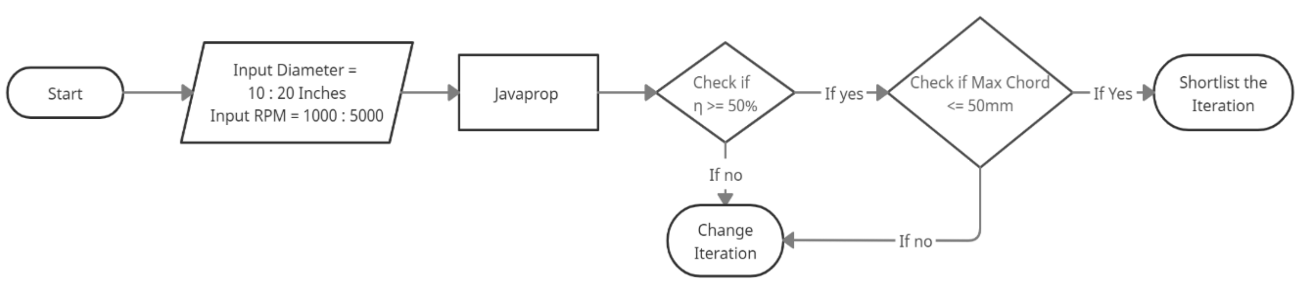

Figure 6: Designing Process

We fixed a constraint on efficiency of 50%, as it is considered a fairly good value at take-off velocity. From figure 7, all the propellers having more than 17 inches diameter satisfied the efficiency constraint.

In the next step, we used maximum chord as the limiting parameter. Considering the manufacturing and structural requirements, the maximum chord of the propeller was fixed at 50 mm.

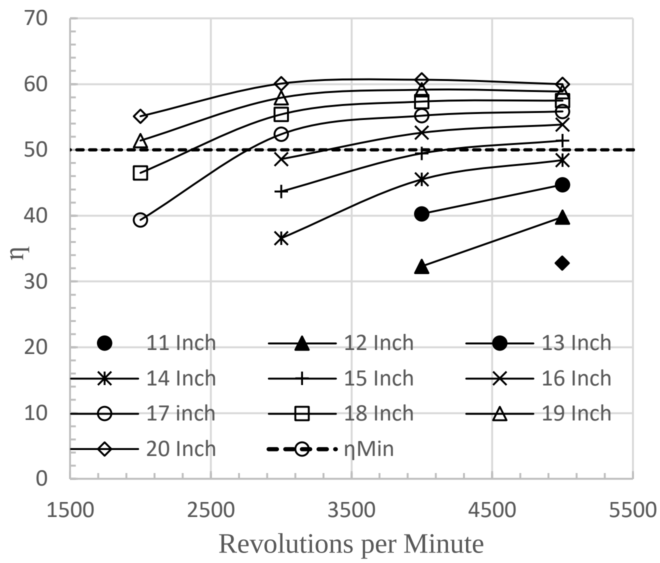

Figure 7: η vs RPM

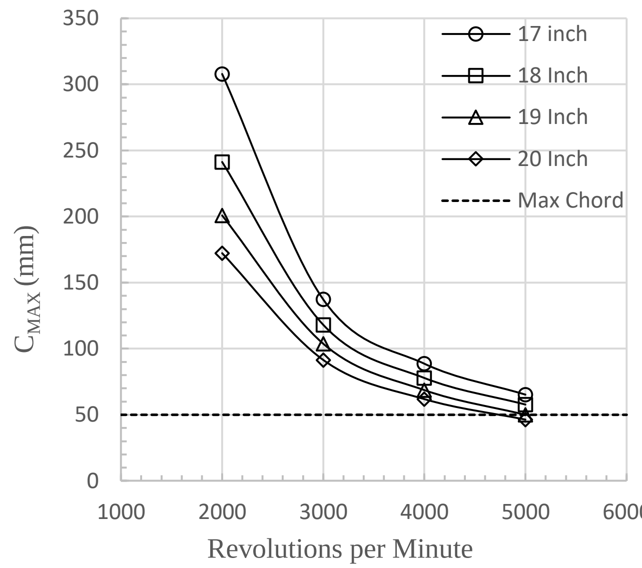

Figure 8: Maximum Chord vs RPM

Using figure 8, propellers of diameters 19 and 20 inch at RPM 5000 were selected at this step.

6.4. Final Design

The propeller with a diameter of **19 inch and a pitch of 10 inch at 5000 RPM** was selected as it:

a. Had the smaller diameter of the two selected.

b. Satisfied the thrust as well as efficiency requirement as per the operating condition.

7. RESULTS

7.1. Propeller Geometry

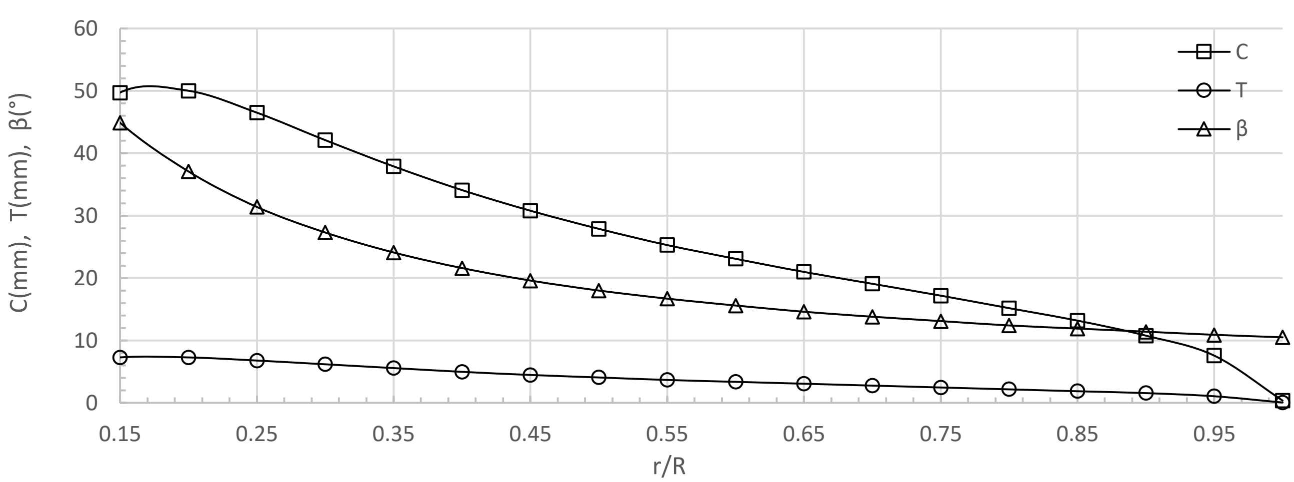

Figure 9: Propeller Geometry

Javaprop optimizes the propeller geometry along radius automatically according to the theory [6].

Figure 9 describes the final geometry of the propeller

7.2. Final CAD Model

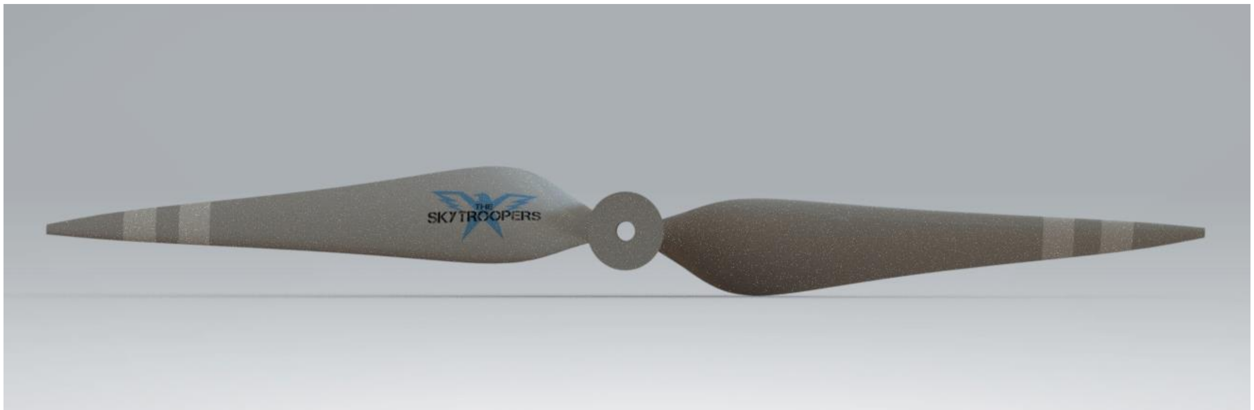

Figure 10: CAD Model

7.3. Performance

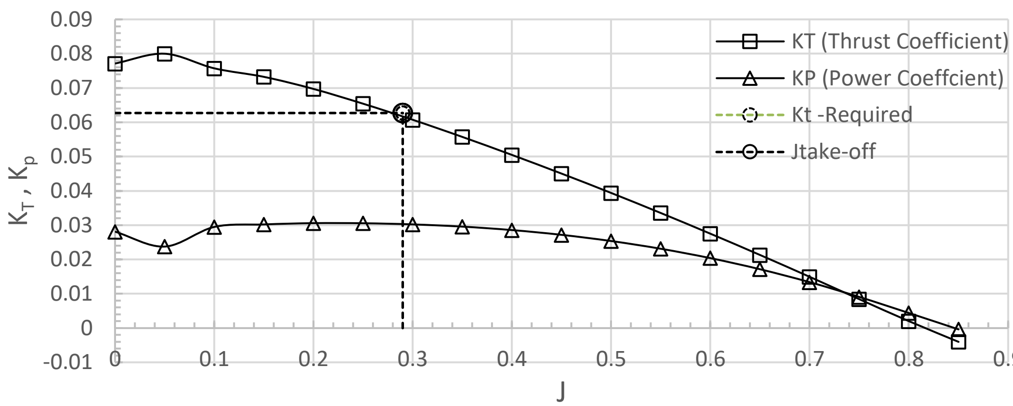

Figure 11: K_T, K_P vs J

Figure 11 shows theoretical values for Performance analysis of the propeller using Javaprop.

7.4. CFD

CFD has been used to get approximate values as the propeller cannot be manufactured and tested. K-ω SST turbulence model is used as it provides better flow characteristics than most RANS model. Also it shows good behavior in complex physics flows and is highly suited for complex geometries (higher curvature).

7.4.1. Meshing

A Hexahedral type of mesh is used as it yields more accurate flow field solutions. Also, this mesh element is highly suited for external fluid flows. As the Reynolds number associated with the geometry is less than 100,000 (viscous force dominates); a $y^+ \approx 1$ has been considered so that the near-wall physics is captured more accurately.

7.4.2. CFD Results

The testing has been done for RPMs ranging from 4000 to 6000 and advance ratios (J) from 0.1 to 0.8. The graph below shows the performance of the propeller. A max efficiency of 80 % or higher was achieved at all RPMs. Also at the design conditions of 11.68 m/s and 5000 RPM an efficiency of 59% is achieved. The data collected is in good consideration with the initial data from Javaprop . But real time testing would be required to check the accuracy of the data.

The pressure contour shows the pressure distribution over the upper (A) and lower (B) surface of the propeller; which concludes that the physics of the propeller is captured properly.

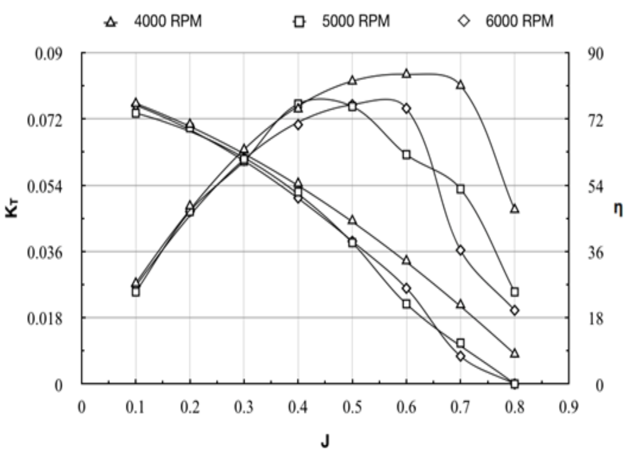

Figure 13: Performance at Different RPMs

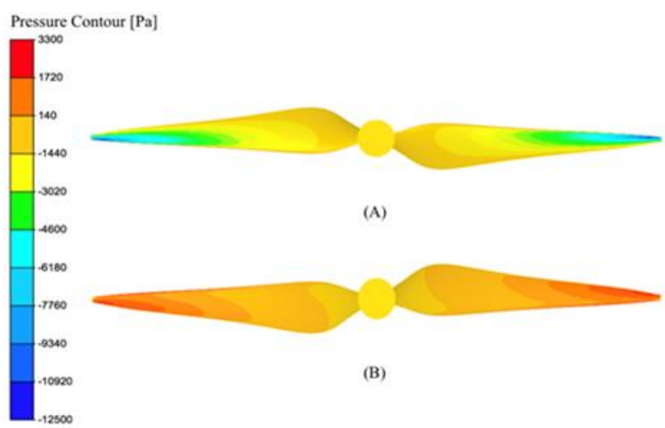

Figure 14: Pressure Contours at Design Conditions

8. MANUFACTURING

8.1. Material Selection

A trade-off based on some parameters was carried out and the results are shown in table 6. The materials differentiated were considered by analyzing the materials used by reputed propeller manufacturers.

Materials	Wood	Composite& Plastic	Reinforced plastics	Long glass Fiber Composite	Carbon Fiber 3k	Glass Fiber
Strength to Weight Ratio	High	Moderate	High	High	High	High
Flexibility	Less	Moderate	Moderate	High	High	High
Able to Handle Vibration	No	Yes	Yes	Yes	Yes	Yes
Weight	Moderate	Low	Low	Low	Low	Low
Cost	Low	High	Low	Low	Moderate	Low
Vibrational Energy Loss	Moderate	Moderate	Low	Low	Low	Low

Table 5: Material Trade-Off

The best material suited is **Glass Fiber** due its better mechanical properties, which allows it to withstand deformation and resist creep under heavy load**.** Glass Fiber is both stiffer and stronger than standard reinforced plastics. The additional stiffness is beneficial to the control of vibration resonance response. The exact names of the materials used is in given by table 6.

Glass Fiber	E-Glass Fiber Cloth 135 GSM
Resin	Lycal 1011

Table 6: Material Used

8.2. Trade-off

Manufacturing Technique	VARTM	Pultrusion	3D printing
Unit Price	Low	High	Low
Product Quality	Moderate	High	Low
Setup-Cost	Low	Very High	High
Mass production	Yes	Yes	No
Complexity	Low	Moderate	Low

Table 7: Manufacturing Processes Trade-off

By observing table 7, Pultrusion is the most suitable process considering mass production and product quality. But the setup cost for Pultrusion is very high as the machinery involved is expensive. On the other hand, considering 'India' as the manufacturing location; Cost of labour is comparatively cheaper.

Thus, **Vacuum Assisted Resin Transfer Moulding (VARTM)** is more logical and practical process to be used for the production of propellers as it is mostly based on manual labor performing each step.

9.3. Manufacturing Process

The team decided to go with Vacuum Assisted Resign Transfer Moulding as the primary manufacturing process for the propeller. It is the one of technologies to fabricate the polymer composites to be used in any industries such as in aerospace, automotive and construction industries.

As shown in the figure 15, VARTM process consists of 5 Steps.

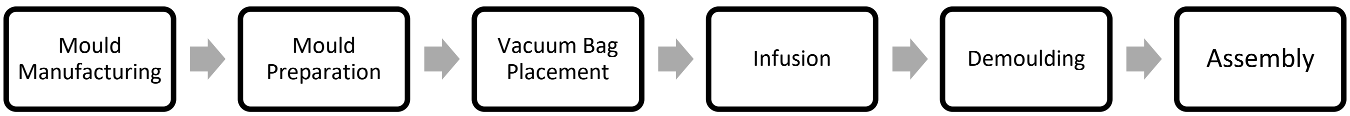

Figure 15: Vacuum Assisted Resin Transfer Moulding

9.3.1. Mould Manufacturing

The process starts with creation of mould using the CAD model. Considering the geometry of the propeller i.e. the blade twist, tapered planform, mould halves can be manufactured by using conventional methods or it can be manufactured using a 3-D printer in wood or composites respectively.

9.3.2. Mould Preparations

In this step, Mould release agent will be applied to the half mold first and then the fiber glass cloth will placed according to the no of layers fixed, as the thickness along the radius of the propeller varies. The number of layers of Glass Fiber is directly dependent upon the geometry of the propeller (Twist, chord variation). The orientation of the fiber will be kept +/- 45° as it provides optimum strength considering the shear forces and bending moment on the propeller during operation.

9.3.3. Vacuum Bag Placement

Once the mold is prepared, it will be placed in the vacuum bag. The plastic bag will airtight with one inlet for Resin and one outlet to remove the excess resin.

9.3.4. Infusion

Once we are done with the second step, the vacuum pump will be turned on. Pressure will be maintained at 70 mm of Hg in the process. During the infusion process, the following resin conditions has to be maintained. Firstly, the resin stock is enough to avoid incoming air bubbles. Secondly, the resin that comes out of the outlet point is kept to be free of air bubbles. This can be done by continuing to run the pump and opening the resin inlet for a while after all the fiber parts have been moistened.

9.3.5. Demoulding

In this step the final part and mould are separated from each other carefully. Use of mould releasing agent in the first step of mould preparation makes sure this step is carried out effortlessly.

9.3.6. Assembly

Two of the finished halves of the propeller will be joined at leading and trailing edges by cold bonding technique with the same glass fiber as the bonding material.

9.4. Costing

Manufacturing the mould is the most expensive step in this process. But in comparison with the setup cost of pultrusion process, it is much lesser. Once the mould is manufactured the only cost that remains is of the resin and glass fiber.

Serial No	Process/Material	Cost (in ₹)
1	Mould Manufacturing	10000-12000
2	E-Glass Fiber Cloth 135 GSM	300-400/m^2
3	Lycal 1011	1000/Kg

Table 8: Costing

9. POSSIBLE ERRORS

Even with the best possible mesh for propeller CFD, the accuracy of the results is not more than 90 to 95% which can result to a possible error in theoretical and practical values. Also, there might occur some errors in manufacturing the propeller considering the level of accuracy of balanced weight distribution required in the two propeller blades. But propeller balancing techniques can be used to resolve this type of error.

10. CONCLUSION

The team was successful in designing a propeller considering the aircraft requirements and optimize it for take-off conditions. We were also able to theoretically design a manufacturing process according to the design created.

11. REFERENCES

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