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Design and Analysis of Propeller

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ABSTRACT: Propeller is the component which is responsible to produce thrust. The cross area of propeller edge is an aerofoil segment which is ordinarily differing from tip to hub in terms of chord or twist distribution. There are many variables for designing the propeller such as pitch angle, flow angle, chord distribution at the blade span and twist distribution. Blade elements theory will be used for designing the propeller. The blade span is divided into number of cross-sectional elements and for each element thrust generated and torque required will be calculated and summed to find total thrust and torque for the propeller. Computer Aided drafting program CATIA V5 is mostly used for entire design procedure of propeller, from aerofoil selection to final part generation.

The outcome of this project forms a strong base for further design and analysis In ANSYS of a propeller and compare it with an experimental solution.

KEYWORDS: Propeller, Elemental Thrust Coefficient, Elemental Torque Coefficient, Advance Ratio, Pitch, Twist angle.

I. INTRODUCTION

A propeller is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the aerofoil-shaped blade, and a fluid (such as air or water) is accelerated behind the blade. Propeller dynamics can be modelled by both Bernoulli's principle and Newton's third law. The hub of the propeller is a solid centre disc, bored for propeller shaft, to which the propeller blades are attached. The most propeller shafts transmit the torque from shaft to propeller through a key, it is a long, slender rectangle of metal along the shaft that fits into the keyway milled into interior of the hub. Propeller blades are the twisted fins or foils that project out from the hub. It is action of blades that drives the aircraft through air. The blade face is the high-pressure side facing the aft, which pushes the fluid. The blade back is the low-pressure side or suction side. Blade root is the point at which blade is attached to the hub. Blade tip is the extreme outermost edge of the blade. The leading edge of the blade is edge of the blade that cleaves the water and the trailing edge is that from which the water streams away.

II. LITERATURE REVIEW

- A. Study of propeller design parameters: Here propeller design parameters and propeller testing methods were known. The propeller manufacturers are trying to increase the delivered power and the system diameter of the propellers to meet all the requirements. Computer Aided Software are used in designing a propeller, from aerofoil selection to final part generation.
- B. Design and analysis of the propeller: The iterative strategies are used to take care of issues of non-linear programming each using the software as they enhance the rate of merging. Some iterations were done based on single variable method. Different aerofoils were taken and iterations were done to get the best aerofoil shape.
- C. Design of optimum propellers: Improvements are made in equations and computational methods of optimising the propellers. It eliminated small angle approximation and some of the light loading approximations prevalent in classical design theory. Momentum losses due to radial flows were estimated by Prandtl and Goldstein momentum loss function. Used Betz condition that a constant displacement velocity across the wake provides the maximum design efficiency.



D. Propeller design procedure and data: This presented the structural details which must be considered in basic design of high-performance aircraft propeller. It is concerned with primary structural elements, loads and methods of analysis. Also mentioned about aerodynamics, weight and cost in achieving the optimum design.

III. WORKING PRINCIPLE AND METHODOLOGY

A. Blade Element Theory

A generally straight forward strategy for foreseeing the execution of propeller is the utilization of blade element theory. In this method the propeller is divided into a number of independent sections along the length. At each section force balance is applied involving 2-d section lift and drag with the thrust and torque produced by the section. At the same time balance of axial and angular momentum is applied. This produces set of non-linear equations that can be solved by iteration for each blade section.

Flow angle = ϕ

Angle of attack = α

Pitch angle = $\beta = \phi + \alpha$

Elemental lift = $dL = 1/2 \rho U^2 (c \cdot dr) C_l$

Elemental thrust = $dT = dL \cos \phi - dD \sin \phi$

Elemental torque = $dQ = (dL \sin \phi + dD \cos \phi) r$

We know the altitude from which the density is known, we know the diameter as well as the cruise speed.

From the geometry we have, $\tan \phi = U / \Omega r$

We assume angle of attack to be 2.5,

so, we can calculate the pitch angle and hence the pitch.

Blade Solidity: Ratio of total blade area to swept area.

$\sigma = Bc / \pi R$

It should be very small than 1, then only blade element theory is valid.

Elemental Thrust Coefficient: $dC_L / dx = ((Bc\pi^2 x^2) / 8R) \psi_T = 3.88 x^2 \sigma \psi_T$

Elemental Torque Coefficient: $dC_Q / dx = ((Bc\pi^2 x^3) / 16R) \psi_Q = 1.94 x^3 \sigma \psi_Q$

Where ψ_T and ψ_Q are the flow parameters, given as

$\psi_T = (\cos^2 \alpha_i / \cos^2 \phi) (c_l \cos \phi_0 - c_d \sin \phi_0)$

$\psi_Q = (\cos^2 \alpha_i / \cos^2 \phi) (c_d \cos \phi_0 + c_l \sin \phi_0)$

Here, $\phi_0 = \phi + \alpha_i$ and $\alpha_i = (\beta - \phi) / ((1 + 8 x \sin \phi) / \sigma a_0)$

Lift Curve slope (a_0) = $c_l \cdot \alpha$

Advance ratio: Ratio of the freestream fluid speed to the propeller tip speed.

$J = U / nD$; n=rps

Thrust coefficient: $C_T = T / (\rho n^2 D^4)$

Torque coefficient: $C_Q = Q / (\rho n^3 D^5)$

From the above theory we can calculate the desired parameters needed for designing a propeller and analyzing its characteristics.

B. Number of Blades

As power and related solidity requirements go up it generally becomes necessary to increase the number of blades in the propeller. With high solidity propellers, blade overlap inboard becomes a problem and recourse must be made to the use of dual rotation types. From a propeller weight point of view, it generally can be shown that the fewer the number of blades the lighter the propeller weight and the lower the cost.

Therefore, no. of blades = 2

C. Airfoil and Chord Selection

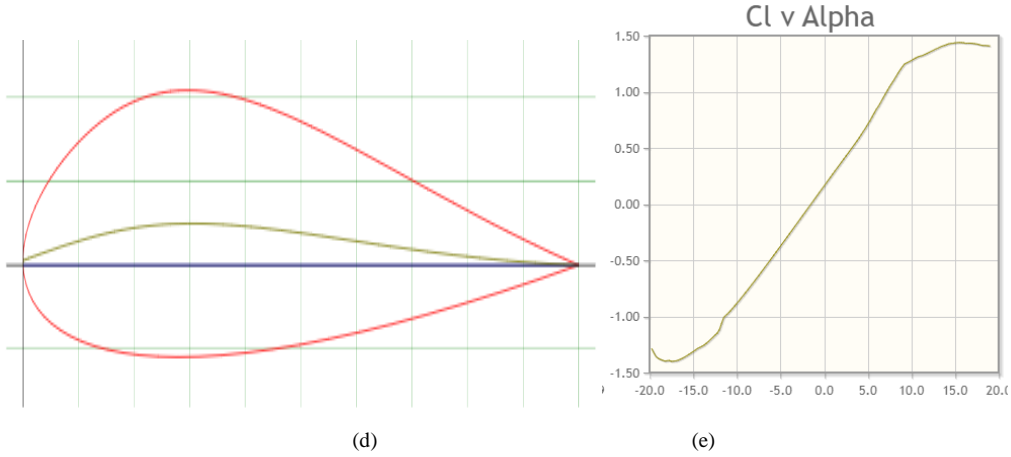


Fig.1. Airfoil selection (a) David Basic B-24 airfoil (b) Lift Curve slope

The specifications of the airfoil we got are:

At $\alpha = 0^\circ$; $c_l = 0.1612$

; $c_d = 0.00611$

At $\alpha = 7.5^\circ$; $c_l / c_d (\text{max}) = 137.5$

Chord selection: It was again calculated using Reynolds number.

$Re = (\lambda U c) / \nu$; $\lambda = (\omega R) / U$; $\omega = 2\pi N / 60 = 125.66 \text{ rads}$

; $R = \text{radius of rotor} = 2.25 \text{ m}$

; $U = 208.33 \text{ m/s}$

; $\nu = \text{kinematic viscosity} = 4.56 \times 10^{-6} \text{ m}^2/\text{s}$ (at 12 km)

IV. CONSTRUCTION AND ASSEMBLY

First and the most important requirement is going through the research papers. We can get the research papers from official sites like google scholar and sci-hub. After going through the research papers and having done all the calculations to determine the design parameters to design the propeller we need a designing software and, in our case, we used CATIA.

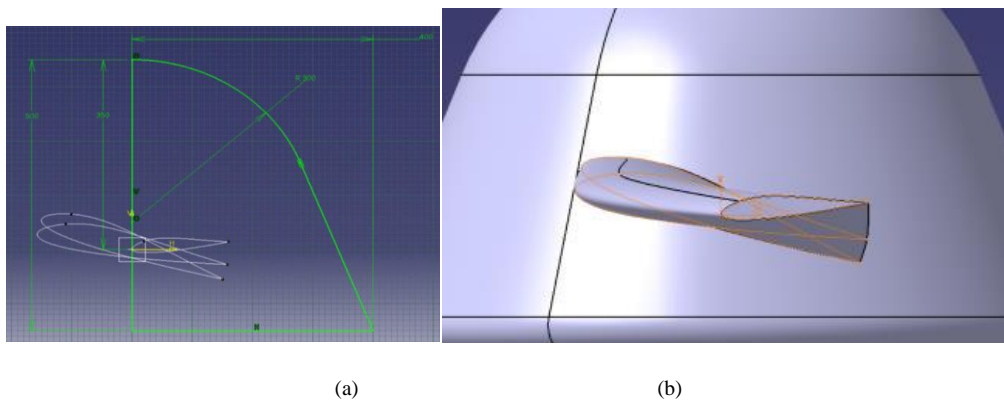
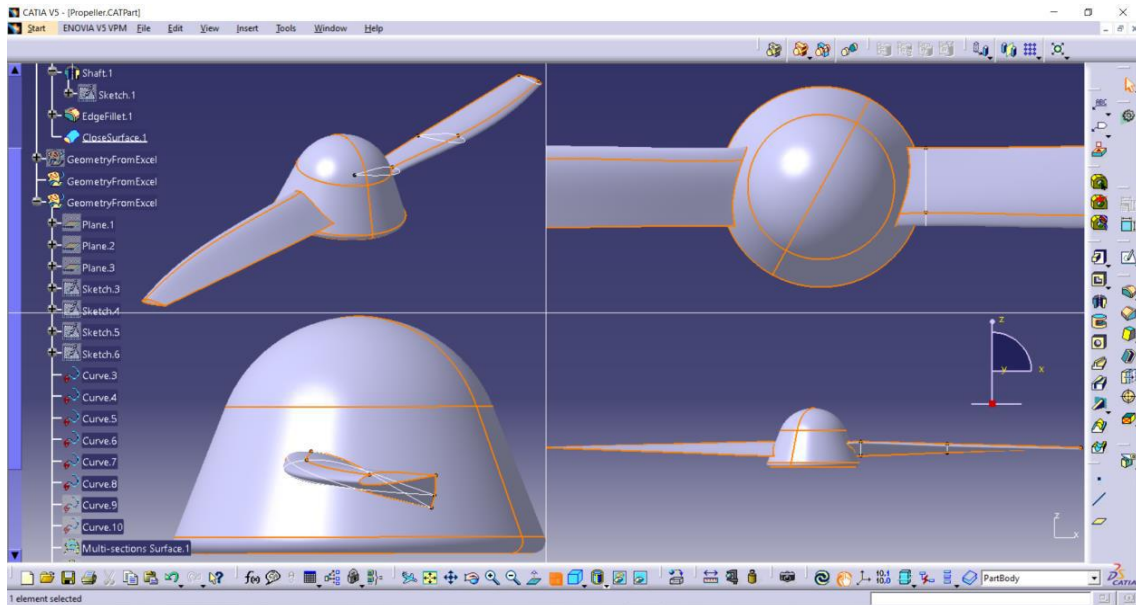


Fig. 2. Catia design (a) Sketching (b) Twist from root to hub

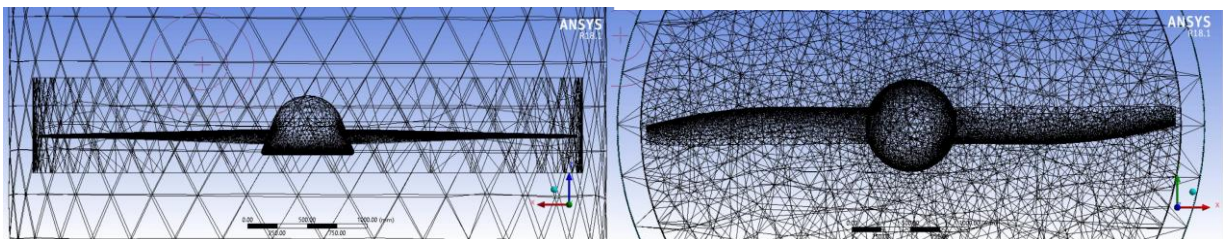


(d)

Fig.3. Design of propeller

V. ANSYS SIMULATION

A. Meshing



(a)

(c)

Fig.4. Meshing

B. Physics

Setup	Brief note
Time	Transient
Model	K-Epsilon (Realizable) – Enhanced Wall Treatment
Boundary Conditions	Inlet – Velocity (Magnitude and Direction) Outlet – Pressure (101325 Pa)

C. Results

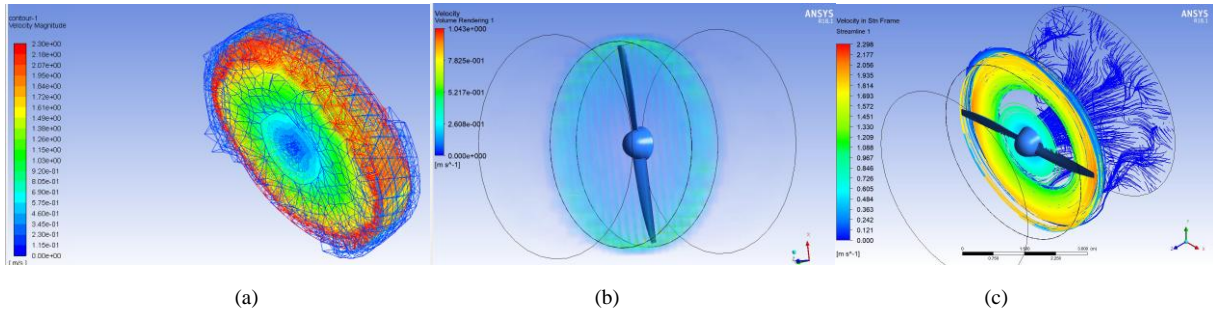


Fig. 5. Results (a) Velocity magnitude (b) Volume rendering (c) Streamline flow

VI. CALCULATIONS

Calculation procedure is iterative.

Specifications:

Cruising speed: 750 km/h

Propeller diameter: 4.5 m

No. of blades: 2

RPM: 1200

Cruise altitude: 12 km (0.312 kg/m^3)

Airfoil selection:

Reynold number (Re): $\rho U D / \mu$; $\rho = 0.312 \text{ kg/m}^3$ (12 km)

; $U = 750 \text{ km/h} = 208.33 \text{ m/s}$

; $D = 4.5 \text{ m}$

; $\mu = 14.22 \times 10^{-6} \text{ kg/ms}$

Reynolds number = 2000000

At this Reynolds number, Airfoils characteristics were chosen.

Chord selection:

Reynolds Number = 2,000,000

Using: $Re = (\lambda U c) / \nu$; $\lambda = \omega R / U$; $\omega = 2\pi N / 60 = 125.66 \text{ rad/s}$

; $R = \text{radius of rotor} = 2.25 \text{ m}$

; $U = 208.33 \text{ m/s}$

; $\nu = \text{kinematic viscosity} = 4.56 \times 10^{-6} \text{ m}^2/\text{s}$ (at 12 km)

Therefore, chord (c) = 0.32 m

Blade element theory:

Assume, $\alpha = 2.5^\circ$

From airfoiltools.com: At $\alpha = 2.5^\circ$; $c_1 = 0.4271$

; $c_d = 0.0056$

So, $dL = 925.35 \text{ dR}$

$dD = 12.26 \text{ dR}$

And, $dT = dL \cos \phi - dD \sin \phi$

$dQ = (dL \sin \phi + dD \cos \phi) r$

Now, $\tan \phi = U / \Omega r$; $\phi = 36.38^\circ$

$\beta = \alpha + \phi = 36.38^\circ + 2.5^\circ = 38.88^\circ$

Therefore, pitch = $2\pi \tan \beta = 11.4 \text{ m}$

Therefore, Elemental thrust and torque, $dT = 1850.26 \text{ dR}$ and $dQ = 106.038 \text{ dR}$



On integrating elemental thrust and elemental torque throughout the blade length,
 $R = 2.25 \text{ m}$

Hence, $L = \int (dL = 925.35 \text{ dR}) = 2082.0375 \text{ N}$

$D = \int (dD = 12.26 \text{ dR}) = 27.585 \text{ N}$

Similarly, $T = 1603.47 \times 2 = 3206.94 \text{ N}$

$Q = 2988.8 \times 2 = 5977.60 \text{ Nm}$

Advance ratio: $J = U/nD$; $n = \text{rps} = J = 2.314$

Thrust coefficient: $C_T = T/\rho n^2 D^4 = 0.0626$

Torque coefficient: $C_Q = Q/\rho n^3 D^5 = 0.00129$

VII. RESULTS

Airfoil: David Basic B-24 airfoil

Chord: 0.32 m

Flow angle: $\phi = 36.38^\circ$

Pitch angle: $\beta = 38.88^\circ$

Pitch: 11.4 m

Lift: $L = 2082.0375 \text{ N}$

Drag: $D = 27.585 \text{ N}$

Thrust: $T = 3206.94 \text{ N}$

Torque: $Q = 5977.60 \text{ Nm}$

Advance ratio: $J = 2.314$

Thrust coefficient: $C_T = 0.0626$

Torque coefficient: $C_Q = 0.00129$

The elemental thrust and torque coefficients are calculated iteratively through the length of the blade for the characteristics.

Blade length X (m)	dC_T / dx	dC_Q / dx
0	0	0
0.25	0.0115	0.00109
0.50	0.0460	0.00874
0.75	0.1036	0.0295
1.00	0.1843	0.0453
1.25	0.1866	0.1364
1.50	0.4147	0.2358
1.75	0.5646	0.3744
2.00	0.7375	0.3622
2.25	0.9334	0.7557

VIII. CONCLUSION

The theoretical results and the results through the analysis may vary because of the errors. The thrust at 12 km was found out to be 3206 N, torque was found out to be 5977 Nm. Increasing number of blades, rpm and the diameter of the propeller can increase the total thrust. The maximum speed occurs at the blade tips far away from the propellers as analyzed through Ansys simulations. Different research papers proposed different theories to design and analyze the propeller, going through them and concluding we sorted out a easy way for designing with the help of our guide.



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We also express my deep sense of regards and thanks to Head of Department. We feel very privileged to have had their precious advices, guidance and leadership.

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