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Design of Airscrew Propeller as an Alternative Main Propulsion for Wing in Surface Effect (WiSE) A2C Using the Simplified Method Approach

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Abstract

This study focused on developing an airscrew propeller as an alternative propulsion system for the Wing in Surface Effect (WiSE) A2C, employing a rigorous and systematic scientific approach. The design and calculation methodology were grounded in the "simplified method" introduced by Hovey. This technique has proven effective for preliminary propeller design despite its reliance on several assumptions and simplifications. This method balances practicality with empirical data, offering a straightforward framework for generating initial design parameters without extensive computational demands. Although the simplified method has limitations, such as its dependence on empirical observations and reduced computational precision, it remains effective for developing foundational design concepts. The study leveraged this approach to create a propeller design that aligns with the aerodynamic and performance requirements specific to the WiSE A2C. The resulting design features an airscrew propeller with an RAF-6 airfoil profile and a diameter of 685 mm. The RAF-6 profile was chosen for its favorable aerodynamic characteristics, including a high lift-to-drag ratio, which is crucial for optimizing propulsion efficiency. This tailored design ensures compatibility with the operational environment of the WiSE A2C, enhancing its overall performance and stability while meeting specific aerodynamic goals.

1 Introduction

The existing transportation modes efficiently leverage the prevailing environmental conditions, but they hold promise for future progress. Enhancing the current transportation systems requires addressing the principal challenges, i.e., 1. The limited speed of movement for waterborne vessels, 2. Significant energy consumption is needed to overcome gravity and facilitate aircraft take-off, landing, and maintenance within designated areas, 3. The constraints imposed by the earth's surface and the diverse terrain encountered during land-based transport operations.

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Practical implementation of principles derived from aero and hydrodynamics provides opportunities for innovating a unique transportation approach that synergistically integrates airspace, waterways, and land surfaces. A Wing in Surface Effect (WiSE) ship exemplifies synergy by operating close to the earth or water surface, utilizing the ground effect. This proximity creates a high-pressure air cushion, reducing drag and increasing lift, enhancing efficiency, reducing power requirements, and improving stability for low-altitude, high-efficiency flight over flat terrains or water [1]. WiSE vessel is defined as a mode that flies close to the ground surface by utilizing the ground effect/surface air compression effect that occurs when the ship is flying low by maintaining a speed adjusted to the weight and design of the vessel [2]. This study aims to provide an alternative propulsion for the WiSE A2C.

Figure 1. Wing in Surface Effect Craft (WiSE) A2C

The WiSE A2C is a wing-in-surface effect vehicle developed by the Agency for the Assessment and Application of Technology - BPPT (now National Research and Innovation Agency (BRIN)). The A2C model is an advancement from the successful Remote Control (RC) model, which underwent flight tests in Jatiluhur in 2008. The development from an RC model to a two-seater human-crewed vehicle poses various challenges, including designing an airscrew propeller that is easy to manufacture using simple methods. To achieve this goal, the calculation and design methodology employed in this study utilizes the "simplified method" approach developed by Hovey [3-5]. This method heavily relies on assumptions and simplifications, which may give it an empirical and speculative impression. However, despite these characteristics, the process remains valid for propeller design in light aircraft and aeromodelling applications. Another advantage of this method is its practicality, particularly for novice designers.

The optimal design of a propeller for a wing in a surface effect ship includes efficient blade shape, appropriate blade angle of attack, and suitable rotational speed [4-5]. Considering these design parameters, the propeller is expected to optimize the efficiency and performance of the vehicle operating in Wing in Ground (WIG) effect conditions. This study adopted a rigorous scientific approach to develop an airscrew propeller as a potential alternative propulsion system for the WiSE A2C. The design and calculation methodologies employed in this research were grounded in the "simplified method" formulated by Hovey, which provides a structured framework for propeller design by incorporating empirical data and theoretical considerations relevant to light aircraft and ground effect vehicles.

2 Experimental Methods

2.1 Schematic process

The flowchart in Figure 2 visually encapsulates the study's abstract, detailing the systematic methodology for developing an airscrew propeller for the WiSE A2C. It delineates the comprehensive process from the initial research focus-formulating an alternative propulsion system, the culmination of the specific design features of the propeller. The flowchart methodically illustrates each critical phase, beginning with adopting a rigorous scientific approach and applying the "simplified method" developed by Hovey. This method was strategically selected for its ability to balance empirical data with practical design requirements, providing a streamlined framework for generating preliminary design parameters with reduced computational complexity [8-10].

Furthermore, the flowchart underscores the critical design considerations integral to the research, such as optimizing aerodynamic efficiency, achieving a favorable lift-to-drag ratio, and ensuring the propeller's compatibility with the operational conditions specific to the WiSE A2C. It provides a clear visualization of how these considerations were integrated into the design process, guiding the development of a propeller with an RAF-6 airfoil profile. This structured approach ensures that the propeller design not only meets the defined aerodynamic and performance objectives but also enhances the overall propulsion system's efficiency, stability, and effectiveness across a range of operational scenarios [11].

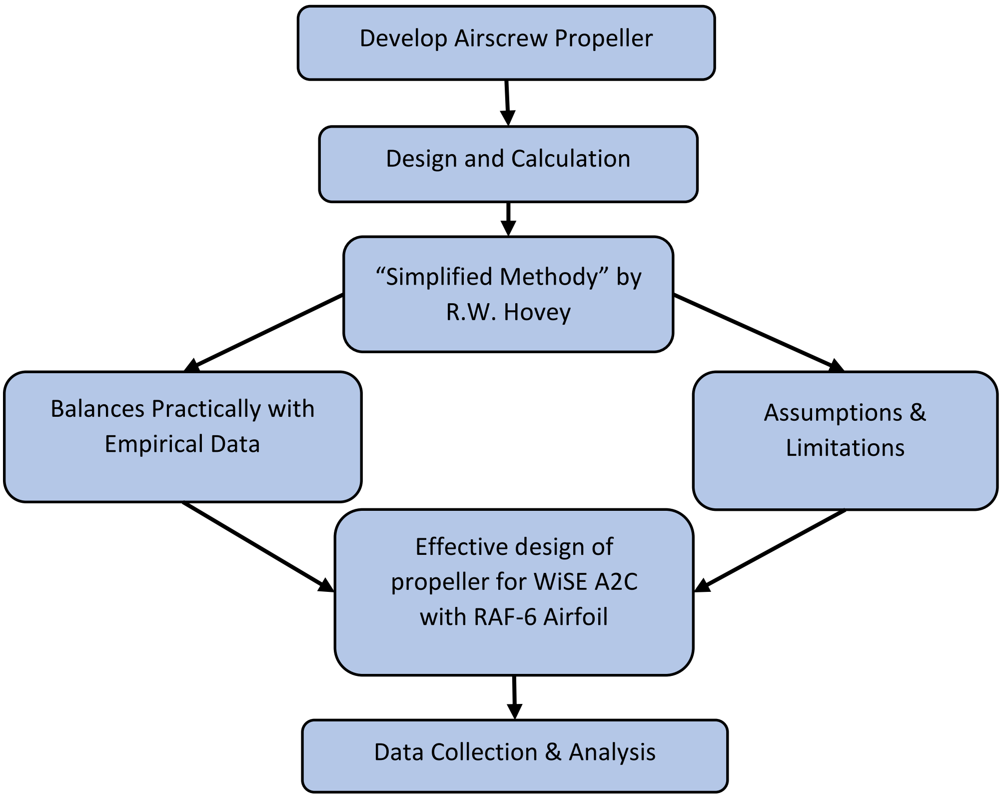


Figure 2. Research flowchart

2.2 Materials

Input parameters are the primary parameters whose values are determined as inputs in the propeller design process [12]. The following are the main parameters that serve as inputs for designing the airscrew propeller for the WiSE A2C.

a) Propeller Diameter (*D*)

The design of the propeller was conducted by considering the lift and drag characteristics, as well as the thrust horsepower and brake horsepower data obtained from the engine selection process. These parameters were instrumental in determining the appropriate propeller diameter [13]. The propeller diameter is set to 4.5 feet or rounded to 1370 mm. The number of propeller blades is set to 8.

b) Propeller Rotation Speed (Revolutions per Minute-*RPM*)

The propeller rotation speed is determined based on data from the main engine that will be used as the prime mover. The selected engine for the main propulsion is the ROTAX Engine, which has the following specifications:

Power max : 141 HP at engine speed 5800 RPM (max. five minutes)

Power take-off : 139.5 HP at engine speed 5800 RPM

Power continuous: 132.8 HP at engine speed 5500 RPM

c) WiSE A2C Airspeed (*V*)

Based on the WiSE A2C design data, the established take-off airspeed is 43 Miles per Hour (MPH) (stall speed), while the cruising airspeed is 63 MPH. The airspeed used as a parameter for propeller design is the take-off airspeed (43 MPH).

2.3 Design parameters calculation

a) Induced Drag (D_i)

The mathematical expression is presented in Equation 1.

$$D_i = K \frac{W^2}{\pi . q . b^2} \tag{1}$$

K = Correction Factor of aerodynamic surfaces. The value of "K" is taken around 1.2.

q = Standard aerodynamic term to express air speed in equivalent ram pressure in Lb/ft^2.

At sea level, the value of *q* is expressed in Equation 2.

$$q_{s.l.} = 25.5 \left(\frac{V}{100}\right)^2 \tag{2}$$

As the altitude is increased, the *q* value will decrease. At 5000 ft., the value of density altitude is calculated by Equation 3.

$$q_{5000} = 22 \left(\frac{V}{100}\right)^2 \tag{3}$$

Since the WiSE A2C operates above sea level, the value of *q* used is the *q* at sea level.

V = Airspeed in MPH. This is identical to the take-off speed of WiSE A2C, which is 43 MPH.

W = The total flying weight of the aircraft in steady flight in pounds.

Based on the WiSE A2C design data, the maximum take-off weight of the WiSE A2C is 772 Lb (corresponding to the displacement of WiSE A2C).

b = Wingspan, the dimension in feet from wing tip to wing tip.

The wingspan of the WiSE A2C is 21.7 ft. Since the WiSE A2C flies above sea level, the value of *q* used is the *q* at sea level. Therefore, the Induced Drag can be calculated using Equation 4.

$$D_i = K \frac{W^2}{\pi . q . b^2} \tag{4}$$

b) Parasite Drag (D_{par})

Parasite Drag can be estimated by calculating the projected area of the WiSE A2C as seen from the front view (with an incidence of 4°). Based on WiSE A2C design data, the total projected frontal area is determined to be 39.73 ft^2.

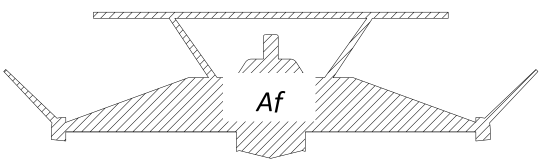


Figure 3. The total projected frontal area of WiSE A2C with an incidence of 4°

Based on the above data, Parasite Drag could be calculated using Equations 5-7.

$$f = A_f \, . \, C_d \tag{5}$$

$$D_{par} = q \, . \, f \tag{6}$$

$$\text{Total Aerodynamic Drag} = D_i + D_{par} \tag{7}$$

Where:

q = Standard aerodynamic. The value of q used is the q at sea level, which is 4.71 Lb/ft^2.

f = Equivalent "Flat Plate Area" in ft^2.

This is the size of a flat plate, held at a right angle to the airstream, that would produce the same parasite drag as your whole aircraft.

f = A_f . C_d

A_f = Total projected frontal area in ft^2.

C_d = Coefficient of drag.

The C_d could be estimated from Figure 4 based on similitude with existing aircraft. The relative streamlining, the length-to-thickness ratio of the fuselage, and freedom from perturbances, struts, or wires are the criteria for selecting a value for C_d. For WiSE, A2C is estimated to have a C_d of 0.1.

c) Total Hydrodynamic Drag (*Rt*)

The hydrodynamic drag calculation method refers to the method developed by Daniel Savitsky for calculating the resistance of planing hull [3,4]. Given the Vee hard chine hull design of the WiSE A2C, which is identical to the hull design of planning hulls, it is highly appropriate to use this method for calculating the hydrodynamic resistance of the WiSE A2C. In his journal article titled "Hydrodynamic Design of Planing Hulls," Savitsky [14] defines the total hydrodynamic drag as presented in Equation 8.

$$R_t = \Delta \tan \tau + \frac{\rho \, V_1^2 \, C_f \, \lambda \, B^2}{2 \, \cos\beta \, \cos\tau} \tag{8}$$

Where:

R_t = Total hydrodynamic drag

Δ = Displacement. The displacement of WiSE A2C was 0.34 tons, and the displacement of the two pontoons was 0.01 tons, so the total displacement became 0.35 tons.

τ = Trim angle of planing area. Under normal conditions, the position of the fuselage is trimmed by the stern with a trim angle of 4°.

ρ = Density of seawater. The density of seawater is 1025 kg/m^3

λ = Mean wetted length-beam ratio. The value of λ for τ = 4° is 1.86.

V_1 = Mean velocity over the bottom of the planning surface .

The mean velocity over the bottom of the playing surface is lower than the velocity at its front section. This is due to the higher pressure on the lower surface than the free-stream pressure in its surroundings (see Equation 9.

$$V_1 = V\left(1 - \frac{0.012 \, \tau^{1.1}}{\lambda^{0.5} \, \cos\tau}\right)^{0.5} \tag{9}$$

V represents the horizontal velocity of the planning surface and is identical to the WiSE A2C's speed, which is 43 MPH = 19.2 m/s.

C_f = Friction drag coefficient

The friction drag coefficient refers to the American Towing Tank Conference (ATTC) Line 1947, developed by Schoenherr. To read the C_f values from the ATTC Line 1947 graph, the Reynolds number must first be calculated by Equation 10 [16].

$$Rn = \frac{V \times Lwl}{\nu} \quad (10)$$

V represents the WiSE A2C's velocity at the start of take-off from the water surface (stall speed), which is 43 MPH or 19.2 m/s. υ denotes the kinematic viscosity of seawater, which is 1.15 x 10^{-6} m^2/s. *Lwl* corresponds to the waterline length, obtained as 5.486 m from the WiSE A2C design. The obtained value of *Rn* is then plotted on the standard skin friction line graph from the ATTC Line 1947, resulting in a C_f value of 0.0021.

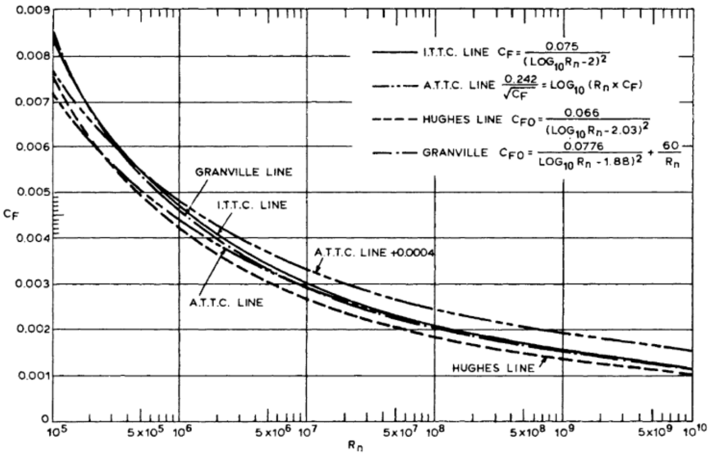


Figure 4. Standard of skin friction line

B = Beam of planing surface. Based on the WiSE A2C design data, a fuselage beam is 0.855 m.

β = Angle of deadrise of planing surface. The WiSE A2C has a Vee hard chine hull shape with a deadrise angle of 13.8°.

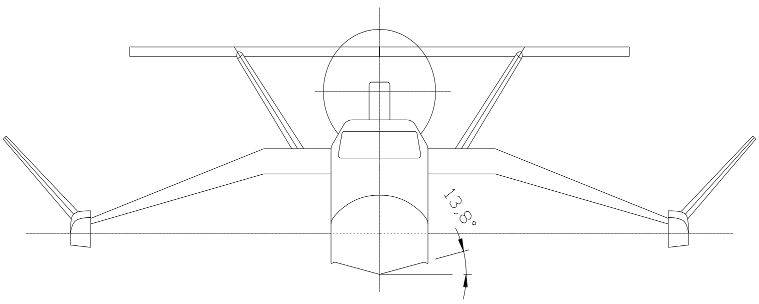


Figure 5. Deadrise angle of WiSE A2C's hull

Based on the obtained data, the total hydrodynamic drag can be calculated using Equation 11.

$$Rt = \Delta \tan \tau + \frac{\rho V_1^2 C_f \lambda B^2}{2 \cos\beta \cos\tau} \quad (11)$$

Therefore, the total drag can be calculated by summing the total aerodynamic drag with the total hydrodynamic drag (see Equation 12).

Total Drag = Total Aerodynamic Drag + Total Hydrodynamic Drag (12)

d) Propeller Shaft Horsepower (SHP)

The mathematical expression is presented in Equation 13.

$$SHP = 0.00267\,\frac{T.V}{\eta} \tag{13}$$

Where:

T = Propeller Thrust in Lb. Taken from the value of the Total Drag, which is 247.51 Lb.

q = Dynamic Pressure or Standard aerodynamic. The value of q used is the q at sea level, which is 4.71 Lb/ft^2.

D = Propeller diameter in ft. The propeller diameter is set to 4.5 ft.

V = Airspeed in MPH. The take-off airspeed of WiSE A2C is 43 MPH.

η = Propulsion efficiency (0.24)

e) Propeller Tip Speed (*TS*)

The mathematical expression is presented in Equation 14.

$$TS = 0.0524 \times D \times RPM \tag{14}$$

Where:

D = Propeller diameter in ft. The propeller diameter is set to 4.5 ft.

RPM = Propeller speed in revolution per minute. The propeller rotation speed after the gearbox is 2283.46 RPM

f) Propeller blade area (A_b)

The mathematical expression is presented in Equation 15.

$$A_b = 2{,}000{,}000\,\frac{T}{D^2.(RPM)^2} \tag{15}$$

This value represents the minimum blade area that must be met to absorb the Shaft Horsepower (SHP) and generate the desired torque and thrust as calculated. This value is further verified with the blade area obtained from the planform. If it does not meet the requirement, iteration of calculations and adjustment of design parameters are performed. If design parameter modifications are made to fulfill this requirement, they may involve increasing the number of blades, the blade width (chord length), or the propeller diameter.

g) Effective Pitch (*EP*)

The mathematical expression is presented in Equation 16.

$$EP = 720\,\frac{V_p}{RPM} \tag{16}$$

V_p = Velocity of air passing through propeller in ft/s.

The velocity of air passing through the propeller (V_p) could be determined using Equations 17 and 18.

$$V_p = (1.47\ V) + V_i \tag{17}$$

$$V_i = \frac{T}{2.94\rho.A_p.V} \tag{18}$$

Where:

T = Propeller Thrust in Lb.

A_p = Propeller disk area (π R^2) in ft^2. By substituting the value of R as 2.25 ft., the value of A_p is calculated to be 15.9 ft^2.

ρ = Air density in slug/ft^3. At sea level, the value of air density is 0.0023 slug/ft^3.
Then:
V_i = 53.55 ft/s
Therefore, V_p could be calculated as follows:
V_p = 115,4 ft/s
Based on the known values of several parameters mentioned above, *EP* could be calculated as follows:
EP = 36.82 inches

h) Effective Pitch Angle (EPA)
The mathematical expression is presented in Equation 19.

$$EPA = tan^{-1} \frac{EP}{2\pi R_{0.75}} \qquad (19)$$

$R_{0.75}$ = The reference station distance at 0.75 of blade radius is measured from the centerline in inches. With a radius (*R*) of 685 mm or 26.97 inches, 0.75 R equals 20.25 inches.
The trigonometric table can be used to obtain the value of EPA. The calculation is as Equation 20.

$$EPA = tan^{-1}\ [0.289] \qquad (20)$$

To find the value of EPA above, the method refers to the Trigonometric table where the tangent value is 0.289, between the angles 16° and 17°. Since the value is not listed in the trigonometric table, it needs to be determined through interpolation, resulting in an angle of 16.1° for the tangent value of 0.289.

i) Chord Line Pitch Angle (β)

The mathematical expression is presented in Equation 21.

$$\beta = EPA + 3° \qquad (21)$$

The value above represents the chord line pitch angle at the station 0.75 of the blade radius. The value of each segment of other radii can be calculated or drawn as the following Figure 6.

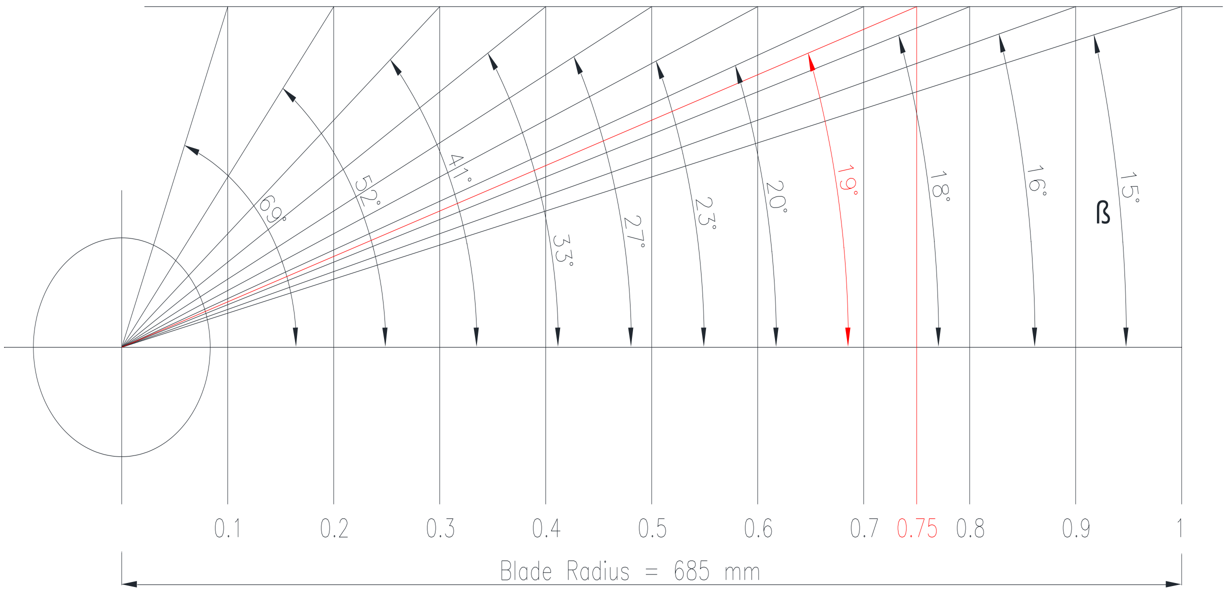


Figure 6. Chord Line Pitch Angle (β) at each radius station

j) Rated Pitch (RP)

The mathematical expression is presented in Equation 22.

$$RP = 2.\pi \,.\, R_{0.75} \,.\, (\tan \beta_{0.75}) \quad (22)$$

Where:

$\beta_{0,75}$ = Chord line pitch angle at station 0.75 of blade radius.

With the above-rated pitch value, the propeller can travel an axial distance of 1118.62 mm in one revolution.

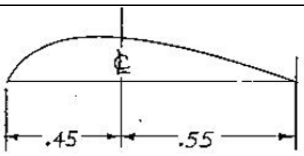
3 Results and Discussion

The fundamental design of the WiSE A2C propeller is based on a platform configuration derived from comprehensive analysis and tabulation of aerodynamic data, explicitly utilizing the RAF-6 airfoil profile. This design process involves the precise calculation of aerodynamic parameters such as chord length distribution, blade twist angles, taper ratio, and pitch distribution, all tailored to optimize aerodynamic performance and efficiency for the specific operational requirements of the WiSE A2C. The selection of the RAF-6 airfoil is based on its advantageous aerodynamic characteristics, including a high lift-to-drag ratio and favorable pressure distribution, which enhance thrust generation while minimizing aerodynamic drag. Table 1 shows blade planform and thickness in this modeling.

Table 1. Blade planform and thickness

Station Along Blade Radius	Chord (% R)	Distance from CL (%R) To * L.E.	Distance from CL (%R) To ** T.E.	Maximum Thickness (% Chord)
0 (center)	-	-	-	-
0.1	-	-	-	-
0.2	14.1	6.3	7.8	31.6
0.3	14.8	6.7	8.1	24.5
0.4	16.3	7.3	9.0	19.1
0.5	17.2	7.7	9.5	16.0
0.6	17.0	7.6	9.4	13.9
0.7	15.6	7.0	8.6	12.4
0.8	13.3	6.0	7.3	13.1
0.9	10.7	4.8	5.9	13.1
1.0 (tip)	7.4	3.3	4.1	14.6

Note:
* CL to L.E. = 45% x Chord at Station
** CL to T.E. = 55% x Chord at Station



Profile section coordinates along the propeller radius can be systematically generated for each section $r/Rr/Rr/R$ using the RAF-6 airfoil coordinates, as detailed in Table 2. This process involves calculating the precise geometric contours of the airfoil at various radial positions along the propeller blade. By employing the RAF-6 airfoil, known for its aerodynamic efficiency, the generated coordinates provide a detailed representation of the blade's cross-sectional shape at each radial location. This allows for accurately determining the blade's aerodynamic properties, such as lift, drag, and moment coefficients, at each section along the radius. The data presented in Table 2 serves as a foundational reference for modeling the aerodynamic behavior of the propeller, ensuring that the blade sections are optimally configured to achieve desired performance characteristics, including maximizing thrust and minimizing drag across the entire operating envelope of the WiSE A2C.

Table 2. Coordinates of RAF-6 Aerofoil for the radius of blade 685 mm at *r/R* = 0.1

Original Coordinate of RAF-6 Aerofoil				**Coordinate of RAF-6 Aerofoil for *R* = 685 mm at *r/R* = 0.1**			
Back		Face		Back		Face	
x	y	x	y	x	y	x	y
0	0	0	0	0	0	0	0
0.02487	0.03599	0.02502	-0.00501	2.141556	11.77774	2.154472	-0.43141
0.04981	0.05408	0.05002	-0.00492	4.289139	17.6977	4.307222	-0.42366
0.09973	0.07426	0.10002	-0.00474	8.58775	24.30161	8.612722	-0.40816
0.19967	0.09062	0.20002	-0.00438	17.19358	29.65543	17.22372	-0.37716
0.29966	0.09578	0.30001	-0.00402	25.80372	31.34404	25.83386	-0.34616
0.39966	0.09534	0.40001	-0.00366	34.41472	31.20005	34.44486	-0.31516
0.49967	0.0917	0.50001	-0.0033	43.02658	30.00886	43.05586	-0.28416
0.5997	0.08406	0.60001	-0.00294	51.64017	27.50867	51.66686	-0.25316
0.69974	0.07142	0.70001	-0.00258	60.25461	23.37222	60.27786	-0.22216
0.79981	0.05378	0.80001	-0.00222	68.87165	17.59952	68.88886	-0.19116
0.89988	0.03314	0.90001	-0.00186	77.48867	10.84508	77.49986	-0.16016
1	0.0015	1	-0.0015	86.11	0.490876	86.11	-0.12917

The table above can be extended to cover sections up to *r/R=1*, enabling a complete representation of the propeller's planform to be constructed, as illustrated in Figure 6. Extending the tabulated data through the entire range of the propeller radius provides a comprehensive set of geometric and aerodynamic parameters for each section along the blade, from the root *(r/R=0)* to the tip *(r/R=1)*. This detailed dataset allows for precise modeling of the propeller's planform, including variations in chord length, blade twist, and taper ratio across the span. By constructing the full planform, designers can ensure that the propeller meets the aerodynamic performance requirements for optimal efficiency and effectiveness in the WiSE A2C application, as shown in Figure 7. This approach accurately replicates the propeller's aerodynamic characteristics, facilitating effective integration into the propulsion system.

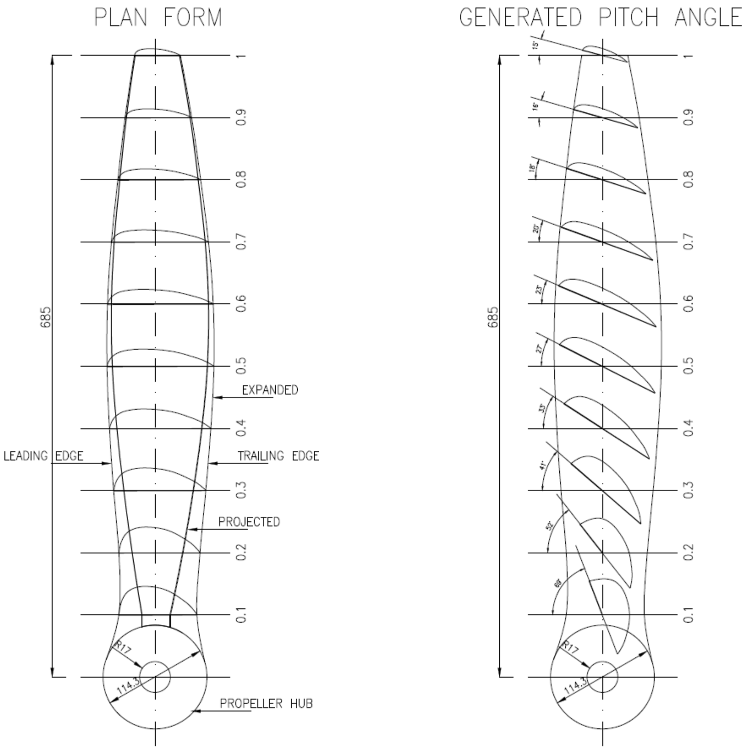


Figure 7. Airscrew propeller planform using RAF-6 profile for the radius of blade 685 mm

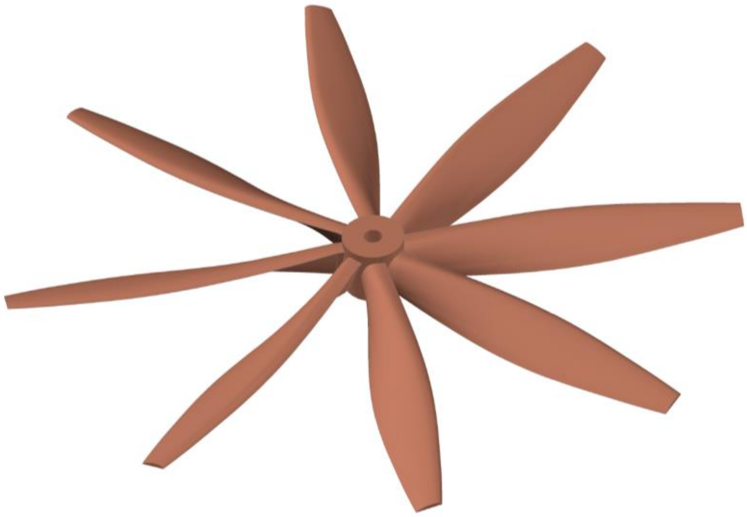


Figure 8. 3D model of 8 – 8-blade airscrew propeller for WiSE A2C

The 8-blade airscrew propeller model designed for the WiSE A2C has a total blade area of approximately 0.467 m^2, which exceeds the minimum required blade area of 0.436 m^2. This ensures the propeller meets and surpasses the minimum blade area specifications necessary for efficient aerodynamic performance. The additional blade area enhances the propeller's ability to generate adequate thrust and absorb the engine's Shaft Horsepower (SHP), thereby contributing to optimal propulsion efficiency. This excess blade area provides a safety margin that can improve overall performance, particularly under varying flight conditions, offering more excellent stability and control while minimizing the risk of aerodynamic stalls or performance degradation.

4 Conclusions

From the research findings, several conclusions were drawn as follows:

1. The engine power required for optimal propulsion was calculated to be 120.1 Horsepower (HP), necessary to achieve the desired performance parameters for the WiSE A2C. To fulfill this requirement effectively, the Rotax 915 iS C24 engine was selected, which provides a maximum output of 140 HP at a rotational speed of 5800 RPM. The engine is equipped with a reduction gear with a ratio of 2.54, which reduces the propeller speed relative to the engine speed. This gearing optimizes the operational efficiency of the propeller, ensuring it functions within its optimal range for thrust generation and torque delivery.
2. The design process led to the selection of an 8-blade propeller configuration to meet specific aerodynamic and performance requirements. This configuration was chosen to ensure that the propeller has sufficient blade area to effectively absorb the Shaft Horsepower (SHP) provided by the engine. The 8-blade design allows for enhanced torque and thrust production, aligning with the aerodynamic characteristics and performance objectives outlined in the design specifications. Additionally, the multiple-blade configuration contributes to maintaining aerodynamic stability and efficiency under varying load conditions.
3. In future work, it is vital to consider selecting a propulsion engine with a slightly lower power output, closer to the calculated requirement of 120.1 HP. This adjustment would enhance power utilization efficiency by minimizing excess power that may lead to unnecessary fuel consumption and weight. Choosing an engine that more closely matches the planned power needs would result in a more optimized propulsion system, improving overall efficiency and, more precisely, meeting the desired performance criteria. Such an approach could contribute to extended operational range, reduced fuel usage, and improved endurance of the WiSE A2C under different operating conditions

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