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Design and Aerodynamic Analysis of Fixed-Wing Vertical Take-Off Landing (FW-VTOL) UAV

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ABSTRACT

This study aims to produce a Fixed Wing-Vertical Takeoff Landing (FW-VTOL) design that has good aerodynamic characteristics on its wing and fuselage. The design process begins with determining the Design Requirement and Objective (DRO). According to DRO, the aircraft is designed to be able to operate at speeds of 14 m/s and an altitude of 120 m (cruise phase) above ground level. The Maximum Takeoff Weight (MTOW) of the planned is estimated using previous research data. Based on calculations, for it to have a flight time of 30 minutes, the MTOW of the FW-VTOL is 5.2 kg. The fuselage and wing of the FW-VTOL design were carried out by referring to the MTOW of 5.2 kg. Three candidate airfoils were proposed, and their aerodynamic characteristics were determined using XFLR5 software. The aerodynamic characteristics of the three proposed fuselage candidates are also calculated. At an angle of attack of 30, the Eppler 66 airfoil produces the most lift coefficient and the lift-to-drag ratio of 0.8775 and 94.152, respectively. While the NACA 4412 and S9000 airfoils create lift coefficients of 0.7963 and 0.7963, respectively. From the calculation of aerodynamic characteristics, the first, second, and third fuselage candidates produce drag coefficient values of 0.1397, 0.1576, and 0.1368, respectively. The aerodynamic characteristics of the airfoil and fuselage are then input into the decision matrix table. As a result, the selected airfoil candidate is Eppler 66, while we choose the fuselage design is the third fuselage candidate.

1. Introduction

UAVs are classifying into two types; namely fixed-wing UAVs and rotary-wing UAVs [1]. Each type has its advantages and disadvantages. Fixed-wing UAV has several advantages, such as high cruising speed and altitude, high efficiency, large cabin, relatively longer flight time, and wide range [2,3]. Behind these advantages, the fixed-wing UAV has disadvantages, such as requiring a wide runway for take-off and landing [4,5]. It is in contrast to the rotary wing type UAV, which can take-off and land vertically, making it suitable for operation in remote areas. The combination of both types of UAV, is called Vertical Takeoff landing (VTOL) UAV [4]. The VTOL UAV was developed to gain the advantages

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of the two types of UAVs by combining the two fixed wing and rotary wing configuration concepts [6].

VTOL UAVs have several types, namely tilt-wing, tilt-rotor, rotor-wing, tail-sitter, and FW-VTOL [7]. Some of these types also have advantages and disadvantages of each. The FW-VTOL UAV uses a quadrotor propulsion system for vertical flights and a fixed-wing propulsion system for cruise flights [8]. Figure 1 shows the FW-VTOL UAV.

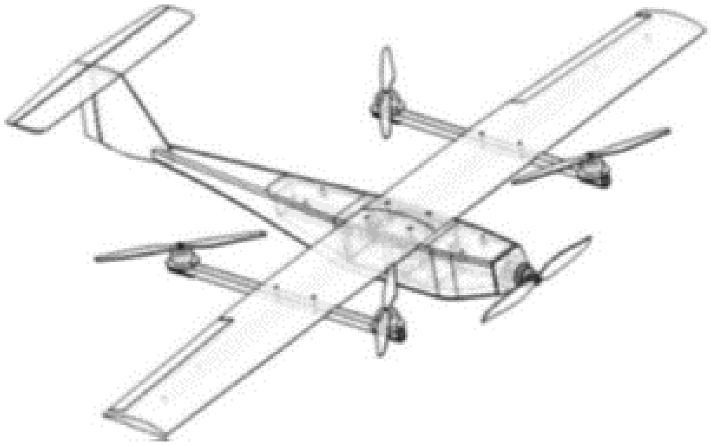


Fig. 1. FW-VTOL UAV [9]

This propulsion combination system makes the FW-VTOL UAV relatively easy to control throughout the mission [10]. In addition, when the flight mode switches from the take-off mode to the cruise mode, the configuration of the two types of propulsion makes the FW-VTOL UAV able to transition smoothly [11]. FW-VTOL UAVs have a weakness in which case of flight time compared to fixed-wing UAVs[8]. Increasing the aerodynamic characteristics of its airframe is one effort that could be accomplished to increase the flight time of the FW-VTOL UAV.

2. Methodology

2.1 Design Requirements and Objectives (DRO)

Design requirements and objectives are the initial design process that is used as a basic reference to determine the mission to be carried out by the FW-VTOL UAV. The mission profile on the FW-VTOL UAV includes the vertical take-off, then transitioning from quadrotor VTOL mode to fixed wing mode during cruise flight, and then transitioning back to the vertical landing. In this study, DRO was determined based on the main problems of previous research. The following are design requirements and objectives established in this study.

i. Flight time is about 30 minutes.
ii. The cruise speed is 14 m/s.
iii. The UAV will perform the monitoring and mapping missions with vertical take-off and landing capabilities.
iv. The altitude is 120 meters above ground level

2.2 Estimation of Maximum Take-Off Weight (MTOW)

The estimation of MTOW used historical data from previous studies. Some historical data on UAVs are demonstrated in Table 1.

Table 1
MTOW vs Flight Time of previous research

UAV	MTOW (kg)	Flight Time (minutes)
Kuzgun [9]	4,7	25,2
Sama VTOL UAV [12]	6,5	60
Inovamap VTOL [13]	8	90
Yangda Sky Fury Electric Long Endurance VTOL Drone [14]	12,5	200
DeltaQuad Pro [15]	6,5	110

MTOW and flight time data in previous studies were used to construct a second-order polynomial regression equation. The independent variable is the flight time and the dependent variable is MTOW. The graph of MTOW versus flight time which is formed based on the second-order polynomial regression equation can be seen in the following Figure 2.

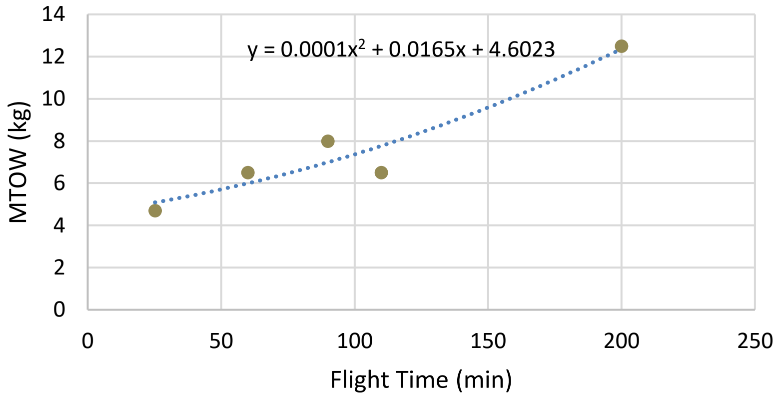


Fig. 2. MTOW vs Flight Time

By the putting the value of flight time (30 minutes) into the regression equation, the FW-VTOL mass can be predicted. The MTOW value of the FW-VTOL UAV is 5.2 kg.

2.3 Wing and Tail Design

The first stage in designing an FW-VTOL UAV is to determine the dimensions of the wing. The FW-VTOL UAV is designed to have an MTOW of 5.2 kg and a high wing configuration. All wing design parameters such as wing loading, wing area, wing span, mean aerodynamic chord, root chord, tip chord, and taper ratio were calculated using following equations [16].

$$W/S_w = \frac{1}{2}\rho V^2 (Cl_{max}) \quad (1)$$

$$AR = \frac{b}{\bar{C}} \quad (2)$$

$$S_w = b.\bar{C} \quad (3)$$

$$\lambda = \frac{c_t}{c_r} \tag{4}$$

$$\bar{C} = \frac{2}{3} C_r \left(\frac{1 + \lambda + \lambda^2}{1 + \lambda} \right) \tag{5}$$

The wing dimensions obtained from the calculation are shown in Table 2.

Table 2
Wing dimensions

Wing Design Parameter	Value
Wing Loading (W/S)	9,545 Kg/m^2
Wing Area (S_w)	0,544762 m^2
Wing Span(b)	1,95 m
Mean Aerodynamic Chord ($\bar{C}$)	280 mm
Chord Root (C_r)	300 mm
Chord Tip (C_t)	220 mm
Aspect Ratio (AR)	7
Taper Ratio (λ)	0,76

The tail is designed to have a v-tail configuration. The tail dimension is calculated using the Eq. (6)-(9) [17-19] and data from Table 2.

$$V_h = \frac{S_h l_h}{S\,\bar{C}} \tag{6}$$

$$V_v = \frac{S_v l_v}{b\,S_w} \tag{7}$$

$$\mathrm{S}_{V-TAIL} = Sv + Sh \tag{8}$$

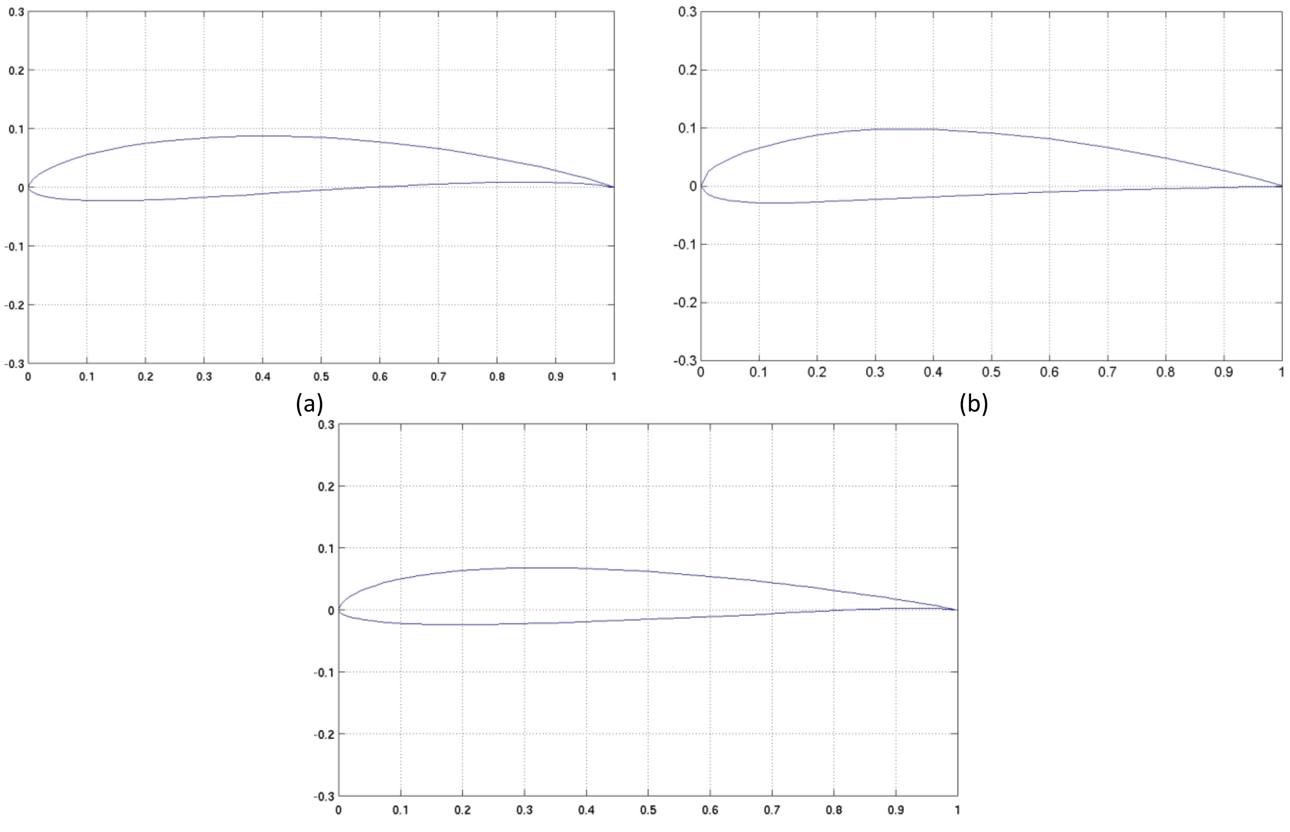
$$\Gamma_{V-TAIL} = tan^{-1}\left(\sqrt{\frac{S_v}{S_h}} \right) \tag{9}$$

The tail dimensions obtained from the calculation are shown in Table 3.

Table 3
Tail dimesion

Tail Design Parameter	Value
V-tail Area	0,1745 m^2
V-tail Angle	38°
V-tail Span	0,72 m
Chord Root (C_r)	300 mm
Chord Tip (C_t)	180 mm

After obtaining the UAV specifications, the next step is to select a candidate for the airfoil to be used. Airfoil candidates were obtained from previous studies, as shown in Figure 3 [20].



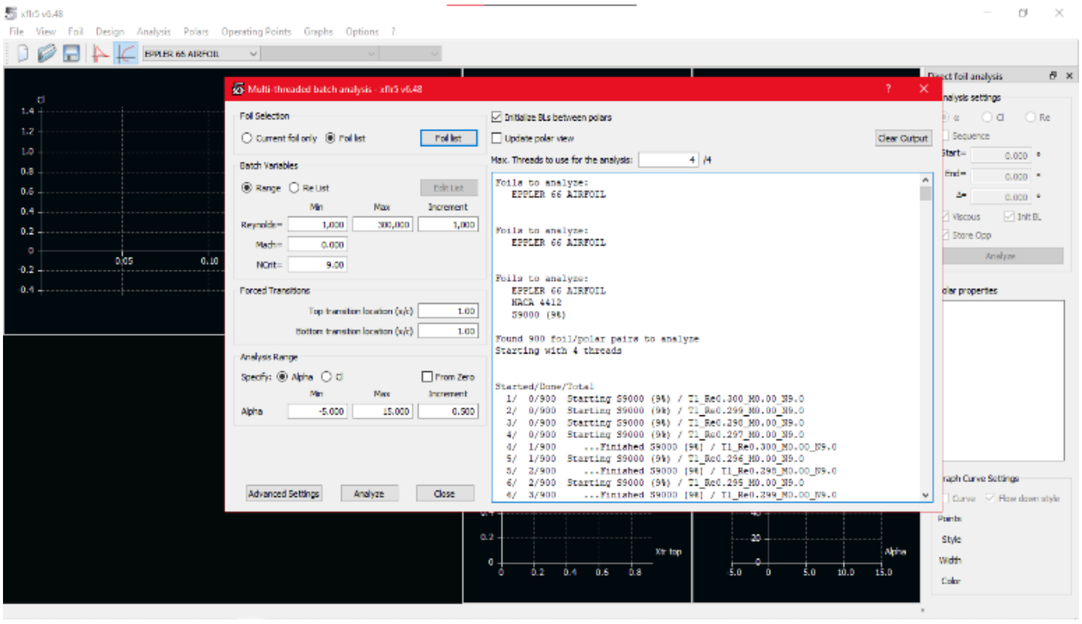
(a)

(b)

(c)

Fig. 3. Airfoil candidates for FW-VTOL UAV (a) Eppler 66, (b) Naca 4412, (c) S9000

Furthermore, the aerodynamic characteristics of the three airfoils above are determined using XFLR 5 software. The parameters obtained through XFLR 5 software are lift coefficient, drag coefficient, and lift-to-drag ratio. In the calculation process, several parameters are inputted, i.e airfoil coordinates, Reynolds number, and variations in the angle of attack [21]. The angle of attack for calculation is selected between -10˚-20˚. Figure 4 shows the calculation process for XFLR 5 Software.



Foil Selection
○ Current foil only ● Foil list

Batch Variables
● Range ○ Re List

	Min	Max	Increment
Reynolds=	1,000	300,000	1,000
Mach=	0.000		
NCrit=	9.00		

Forced Transitions
Top transition location (x/c) 1.00
Bottom transition location (x/c) 1.00

Analysis Range
Specify: ● Alpha ○ Cl ☐ From Zero

	Min	Max	Increment
Alpha	-5.000	15.000	0.500

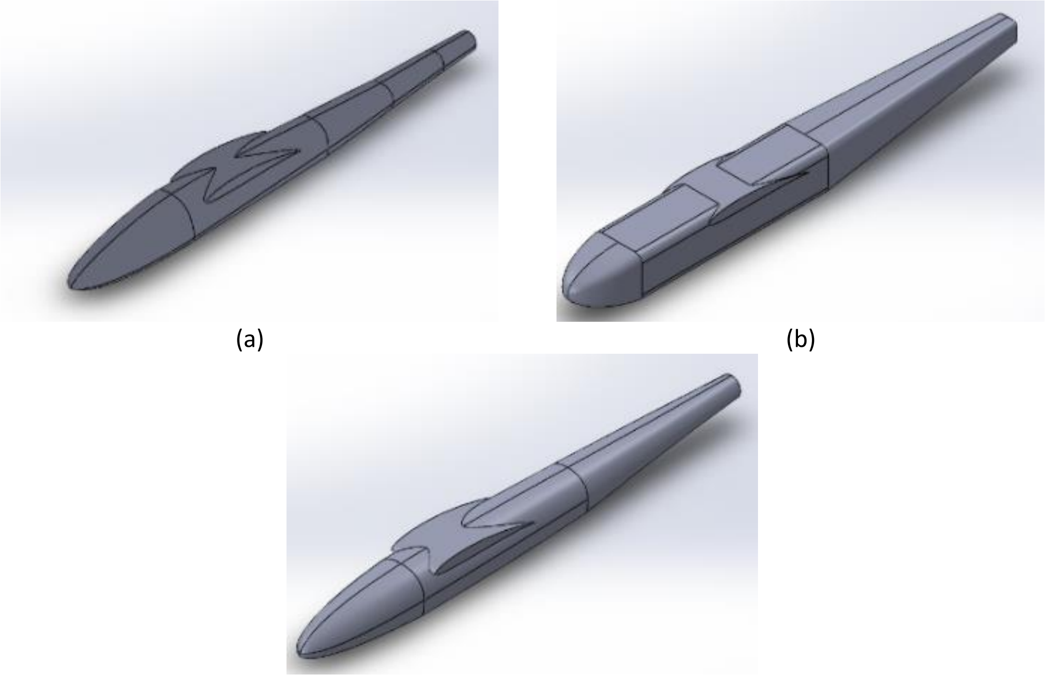
☑ Initialize BLs between polars
☐ Update polar view
Max. Threads to use for the analysis: 4 /4

```
Foils to analyze:
   EPPLER 66 AIRFOIL


Foils to analyze:
   EPPLER 66 AIRFOIL


Foils to analyze:
   EPPLER 66 AIRFOIL
   NACA 4412
   S9000 (9%)

Found 900 foil/polar pairs to analyze
Starting with 4 threads


Started/Done/Total
  1/   0/900  Starting S9000 (9%) / T1_Re0.300_M0.00_N9.0
  2/   0/900  Starting S9000 (9%) / T1_Re0.299_M0.00_N9.0
  3/   0/900  Starting S9000 (9%) / T1_Re0.298_M0.00_N9.0
  4/   0/900  Starting S9000 (9%) / T1_Re0.297_M0.00_N9.0
  4/   1/900      ...Finished S9000 (9%) / T1_Re0.300_M0.00_N9.0
  5/   1/900  Starting S9000 (9%) / T1_Re0.296_M0.00_N9.0
  5/   2/900      ...Finished S9000 (9%) / T1_Re0.298_M0.00_N9.0
  6/   2/900  Starting S9000 (9%) / T1_Re0.295_M0.00_N9.0
  6/   3/900      ...Finished S9000 (9%) / T1_Re0.299_M0.00_N9.0
```

Fig. 4. Calculation Process of XFLR 5 software

2.4 Fuselage Design

The three fuselage designs were created using Autodesk Inventor. The three fuselage candidates have dimensions of length, width and height of 1300 mm, 140 mm and 100 mm, respectively. The three fuselage candidates are shown in Figure 5.


(a) (b)

(c)

Fig. 5. Design of fuselage candidates, (a) The first candidate, (b) The second candidate, (c) The third candidate

Carbon composite material with a density of 1.42 g/cm^3 was used as a candidate for the fuselage design. The three fuselages have a wall thickness of 1.5 mm. Based on calculations on the Autodesk Inventor software, the mass of the first, second, and third fuselage candidates were 1093.45 grams, 1384.33 grams, and 1207.47 grams, respectively. Furthermore, the drag coefficient of the three candidates for the fuselage is calculated through an airflow simulation process. The calculation is carried out in the cruise phase with an angle of attack of 0˚. The selected fuselage design uses a decision matrix from the calculated mass and drag coefficient. The following Table 4 lists some of the parameters used in determining boundary conditions.

Table 4
Simulation parameters

Parameter	Value
Solver Type	Pressure-based
Velocity Formulation	Absolute
Density	1.2099 Kg/m^3
Viscosity	1.846 x 10^{-5} Kg/m.s
Temperature	287.16 K
Velocity	14 m/s
Operation Pressure	101325 Pa
Velocity	14 m/s
Operation Pressure	101325 Pa

2.5 Decision Matrix

The decision matrix table is used to select the best airfoil design candidates. The maximum lift coefficient and lift coefficient at the angle of attack 30 (cruise phase) from the calculation of the airfoil candidate will be compared with the lift coefficient required by the FW-VTOL UAV. If only one airfoil meets the criteria, the airfoil selection process does not need a decision matrix table. Meanwhile, if more than one airfoil meets the criteria, the decision matrix table will be used for the selection process by considering the criteria for lift coefficient, drag coefficient, lift-to-drag ratio, and airfoil thickness.

To select the best candidate for the fuselage, also use the decision matrix table. Selection of the best fuselage candidate by considering several criteria, namely drag coefficient, total mass, and ease of fabrication. The best fuselage design will be used to create the complete FW-VTOL UAV design.

3. Results

3.1 Aerodynamic Characteristics of Airfoil Candidates

The characteristic aerodynamics calculation of the three airfoil candidates was carried out at a speed of 14 m/s (cruise) with a Reynolds number of 255 977. Figure 6 and Figure 7 show the results of the lift coefficient and drag coefficient, respectively.

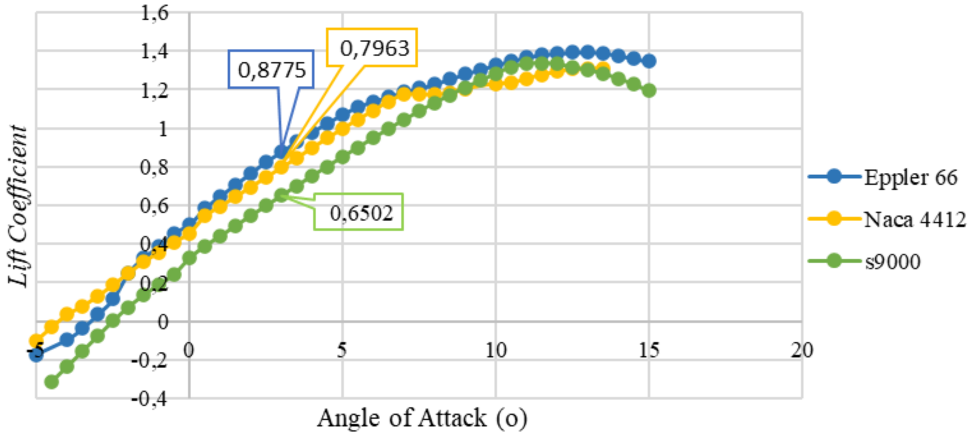


Fig. 6. Lift coefficient airfoil

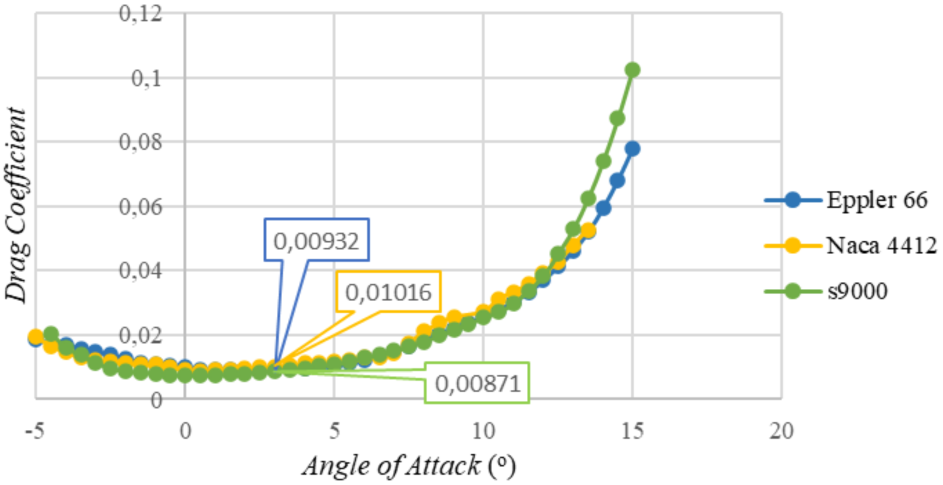


Fig. 7. Drag coefficient airfoil

Figure 6 shows the lift coefficient for each candidate airfoil. The lift coefficients of the Eppler 66, NACA 4412, and S9000 airfoil at an angle of attack of 3˚ are 0.8775, 0.7963, and 0.7963, respectively. Compared to the required lift coefficient of at least 0.790 (angle of attack 3˚), it is seen that the three airfoils meet the lift coefficient requirement. Therefore, the selection of the best airfoil candidate must use a decision matrix table. Figure 7, shows that the Airfoil S9000 has the smallest drag coefficient value at an angle of attack of 30. Figure 8 shows the results of the lift drag to the ratio for each candidate airfoil.

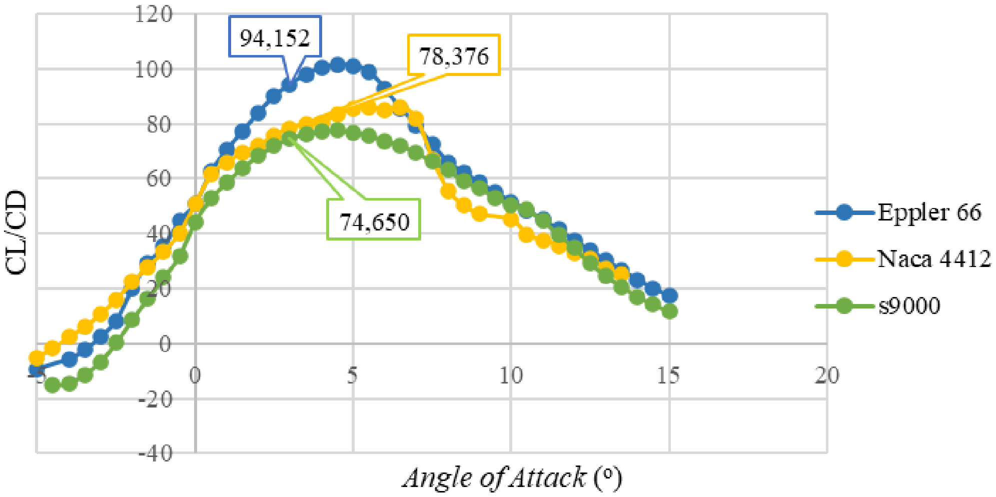


Fig. 8. Lift to drag ratio

Figure 8 shows the value of the lift-to-drag ratio for each airfoil candidate. Airfoils with lift-to-drag ratio from highest to lowest are Eppler 66 (94,152), NACA 4412 airfoil (78,376), and S9000 airfoil with 74,670. It shows that Eppler 66 airfoil has the highest glide ratio. The glide ratio will affect the flight time of the FW-VTOL UAV [22]. The calculation results of the aerodynamic characteristics of the three airfoils are then inputted into the decision matrix table. Apart from these data, the airfoil thickness is also used as an aspect of consideration to determine the airfoil to be used. Table 5 shows the decision matrix table for airfoil selection.

Table 5
Decision matrix for airfoil candidates

Parameters	Weight (%)	Eppler 66	NACA 4412	S9000
Lift coefficient	30	3	1	2
Lift to Drag Ratio (3°)	30	3	1	2
Drag coefficient	30	2	1	3
Thickness	10	2	3	1
Total	100	2,6	1,2	2,2

The percentage of each parameter, such as lift, lift drag ratio, and drag coefficient is set to have the same value, which is 30%. It is because three factors are intertwined with each other and affect the performance of the FW-VTOL UAV. From Table 5, it can be seen that the Eppler airfoil has the largest total score of 2.6. The Eppler 66 airfoil has the highest score of 3 for lift coefficient because Eppler 66 produces the highest lift coefficient at an angle of attack of 30. The Eppler 66 airfoil has also the best value of 3 for the lift to drag ratio parameter because it produces the highest lift drag to ratio at an angle of attack of 3o than other airfoils. On the drag parameter, Eppler 66 has a score of 2 because its drag coefficient is smaller than NACA 4412 but larger than S9000. Furthermore, the thickness parameter of the Eppler 66 has a score of 2 because its thickness is smaller than NACA 4412 but larger than S9000. Therefore, based on the total score, the Eppler 66 was chosen to be the airfoil used for the FW-VTOL UAV.

3.2 Aerodynamic Characteristics of Fuselage Candidates

Aerodynamic characteristics calculation of fuselage candidates uses several meshing sizes, namely 6 mm, 7 mm, 8 mm, 9 mm, and 10 mm. The results of the aerodynamic characteristics of the fuselage candidate produce the drag coefficient. The drag coefficient of each fuselage candidate is shown in Table 6.

Table 6
Drag coefficient of fuselage candidates

Meshing (mm)	Drag Coefficient		
	The first candidate	The second candidate	The third candidate
6 mm	0,1397	0,1576	0,1368
7 mm	0,1389	0,1603	0,1358
8 mm	0,1393	0,1596	0,1379
9 mm	0,1396	0,1592	0,1350
10 mm	0,1391	0,1588	0,1338

Table 6 shows that the fuselage candidate that has the smallest drag coefficient value is the third candidate. At 6mm meshing, the third fuselage candidate has a drag coefficient value of 0.1368. The calculation results of the drag coefficient, total mass, and ease of fabrication are then inputted into the decision matrix table. These values will be used as a consideration to determine the best fuselage candidate. Table 7 shows the decision matrix for fuselage design.

Table 7
Decision matrix for fuselage candidates

Parameter	Weight (%)	The first candidate (Fuselage 1)	The second candidate (Fuselage 2)	The third candidate (Fuselage 3)
Drag coefficient	50	2	1	3
Mass	25	3	1	2
Ease of fabrication	25	1	3	1
Total	100	2	1,5	2,25

The percentage of each parameter is set to the highest (50%). Since the drag coefficient is the main factor affecting the flight efficiency of the FW-VTOL UAV, its value is 50%. In the drag coefficient parameter, the third candidate gets the largest score (3) because the drag coefficient is the smallest of the other candidates. Furthermore, on the total mass parameter, the second candidate gets the highest score because it has the smallest mass compared to other airframe candidates. In the fabrication parameters, candidate 3 and candidate 1 get low scores because the geometry is relatively complicated to make. In general, Table 7 shows that the third airframe candidate has the highest score of 2.25. Therefore, the third fuselage was chosen as the fuselage design to be used.

3.3 The Complete Design of the FW-VTOL UAV

The complete design of the FW-VTOL UAV is based on the dimensions and fuselage parts (airfoil and fuselage) that have been obtained in the previous stage. The 3D design uses Autodesk Inventor software made up of the wings design, fuselage, tail, and VTOL frame. Figure 9 shows the complete design of the FW-VTOL UAV.

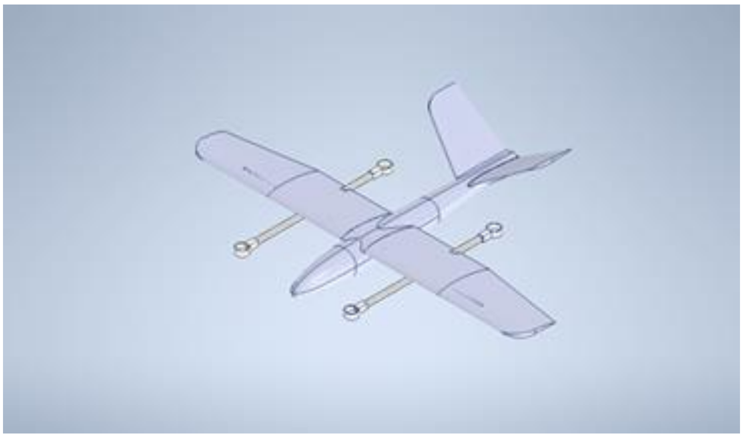


Fig. 9. The Complete design of FW-VTOL UAV

4. Conclusions

The VTOL UAV was developed to gain the advantages of the two types of UAVs by combining the two fixed wing and rotary wing configuration concepts. Based on the research conducted, the following conclusions are obtained

i. The design of the FW-VTOL UAV airframe has been successfully carried out with MTO and wingspan of 5.2 kg and 1.95 m, respectively.
ii. The UAV is designed using Eppler 66, the third fuselage candidate, a high wing configuration, and a v-tail tail configuration.
iii. The lift coefficient and the drag coefficient of Eppler 66 airfoil at an angle of attack of 3° are 0.8775 and 0.00932, respectively.
iv. The drag coefficient of the third candidate fuselage is 0,1368

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