Rapid Preliminary Sailplane Design using Regression Method

Mohamad Yamin*, Ahmad Fakhri Giyats

Abstract—The article describes a new method for the preliminary design of a Sailplane based on technical data from similar Sailplanes, enabling quick design using regression methods. The authors chose FX 66-168 as the main wing airfoil for a new sailplane with a gross weight of 602 kg with a flight parameter Angle-of-Attack (AoA) 0^0 in minimum velocity of 49.5 m/s to cruise. As an example, we illustrate the proposed regression method. Our method allows for improving the effective preliminary design of the sailplane. The effectiveness evaluation validation of the new model is conducted with the numerical calculation using XFLR Opensource software. The research results improve design techniques and could be used as a manual for an aircraft designer.

Index Terms—rapid preliminary design, regression method, sailplane, XRLF5

I. INTRODUCTION

IN 1906, the glider sport developed very rapidly. Supported by scientific evidence conducted by Austrian Robert Kronfeld, who revealed that thermal lift could increase the glider's height, until now, gliders have been widely used for sport, competition, flight training for military and civil aviation pilots, and as a means of aerial recreation.

Based on the history and current conditions described above, efforts are needed to develop aviation technology, especially glider aircraft in Indonesia. This effort can be made from simple steps, namely designing a glider model, to understand how glider aircraft's design concept is. This design process aims to obtain geometry and configuration data from the design glider, flight stability data, and flight performance data.

Flight performance depends on atmospheric characteristics and is usually defined as a number such as pressure, density, temperature, compressibility, kinematic viscosity, and inertia. In addition, these parameters have a description of gravity, which depends on variations in altitude [1].

Atmospheric standards for flight data generally refer to the International Civil Aviation Organization (ICAO) [1]. The standard atmosphere can be used as the boundary condition of the simulation process so that the cost of the experimental study can be minimized.

In March 1999, Dipl. Ing. Klaus Holighaus at the Schempp-Hirth Factory proposed a standard cirrus design. This sailplane concept was built with a wingspan of 15 m without flaps. This aircraft was made with two different types of airfoils. The glide ratio for this glider is 1:37, with a maximum speed of 220 km/hour. Until today, standard cirrus is still used and is currently considered one of the best glider designs in professional competition [2].

The cirrus sailplane is designed with two different airfoils. One of the examples of a cirrus sailplane is FX 66-27 ALL-182, designed by Dr. FX Wortmann at the University of Stuttgart [3]. Later, computer-aided software is employed to assist glider designs in improving performance [4].

This paper aims to validate quick regression methods used in an aeroplane concept design with the objective of minimizing the design process time.

The simple sailplane design concept itself is not new. One of the critical sailplane design processes is the preliminary study. Preliminary design is a fundamental concept for determining parameter values such as empty weight and take-off weight and comparing it with existing data so that the design process can be accelerated. The main sailplane parts are the fuselage, wings, and empennage. These include ailerons and lift and drag devices, such as spoilers, dive breaks, and flaps [4]. Fig.1 presents the characteristics of the aircraft based on its class. Elementary solid equation design is used in fuselage design [5] to calculate the fuselage's surface and volume.
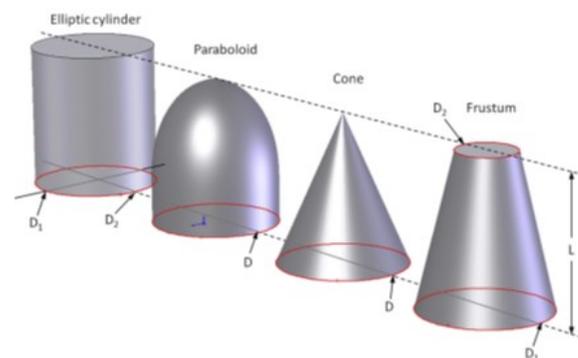
Fig. 1. Elementary solid [5].

The elementary solid calculations are given by the following equations [5].

Parabolic

Surface Area Parabolic

$$S_P = \frac{\pi D}{12 L^2} \left[\left(4L^2 + \frac{D^2}{4} \right)^{1.5} - \frac{D^3}{8} \right]. \tag{1}$$

Parabolic Volume

$$V_P = \frac{\pi D^2 L}{8}. \tag{2}$$

Frustum

Surface Area Frustum

$$S_F = \frac{\pi (D_1 + D_2)}{2} \sqrt{L^2 + \frac{D_1^2 - D_2^2}{4}}. \tag{3}$$

The authors are with the Mechanical Engineering Department, Gunadarma University, Jl. Margonda Raya 100, Depok, West-Java, Indonesia 16424 (Corresponding Author's email: mohay@staff.gunadarma.ac.id).

TABLE I
CHARACTERISTICS OF THE TYPE OF AIRCRAFT BASED ON CLASS [9]

	LSA	GA Aircraft	Sailplanes	Commuter Propliners	Bizjet	Commercial Jetlines
Wingspan, ft	17 - 35	30 – 45	35 – 101	45 – 100	44 – 70	90 – 290
Wing Area, ft^2	75 – 160	150 – 400	120 – 250	300 – 860	200 – 1400	900 – 10000
Wing Aspect Ratio	5 – 12	6 – 11	10 – 51	6 – 13	5 – 12.8	7 – 10
Wing Taper Ratio	0.5 – 1	0.3 – 1	0.4 – 0.5	0.35 – 1	0.3 – 0.5	0.2 – 0.5
HT Aspect Ratio	3 – 5	3 – 5	5 – 7.7	3 – 6	4.5 – 6.5	3 – 4
HT Taper Ratio	0.5 – 1	0.3 – 1	0.5 – 1	0.5 – 1	0.4 – 0.7	0.3 – 0.7
VT Aspect Ratio	0.7 – 3	1 – 2	1 – 3	1 – 3	1 – 3	1 – 3
VT Taper Ratio	0.3 – 1	0.5 – 1	0.5 – 1	0.5 – 0.9	0.4 – 0.9	0.5 – 1
Empty weight, lb$_y$	200 – 800	800 – 3000	100 – 1100	7000 – 26000	700 – 50000	40000 – 550000
Gross Weight, lb$_f$	400 – 1430	1500 – 12500	280 – 1700	12000 – 55000	20000 – 100000	75000 – 1300000

Frustum Volume

$$V_F = \frac{\pi L}{12}(D_1^2 + D_1 D_2 + D_2^2). \quad (4)$$

Cone

Surface Area Cone

$$S_C = \frac{\pi D}{2}\left[\frac{D}{2} + \sqrt{L^2 + \frac{D^2}{4}}\right]. \quad (5)$$

Cone Volume

$$V_C = \frac{\pi D^2 L}{12}. \quad (6)$$

In designing a sailplane wing, several considerations are needed. Several types of wing shapes used in sailplane design are rectangular, tapered, rectangular/tapered, and double or triple-tapered, as shown in Fig. 2.
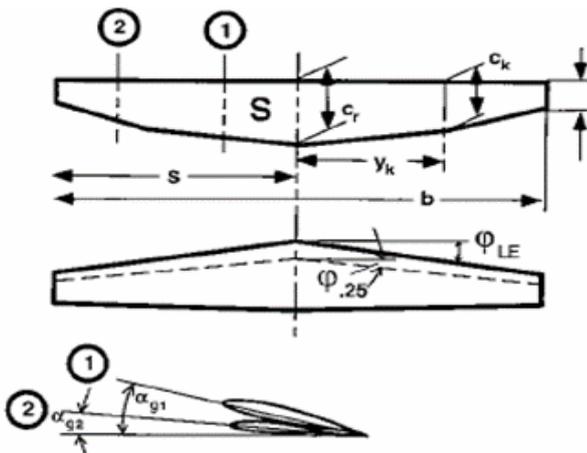
Fig. 2. Wings geometry [13].

The geometry parameter of the wing can be calculated from the following equations [13]:

Aspect Ratio

$$AR = \frac{B^2}{S}. \quad (7)$$

Taper Ratio

$$\lambda = \frac{C_t}{C_r}. \quad (8)$$

Aerodynamic force is the result of pressure and friction acting on the aircraft's surface [1]. The total aerodynamic force that occurs on a wing or airfoil can be transferred in the form of a component perpendicular to and parallel to the flow velocity and the moment from a defined reference point. Three quantity data, namely lift, drag, and pitching moment, need to be carefully considered. The pitching moment is the reference point on the airfoil (Xd), usually at 1/4 chord point. The illustration of lift, drag, and pitching moment are depicted in Fig. 3.
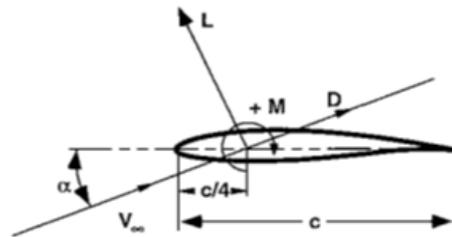
Fig. 3. Aerodynamic force & moment on the airfoil [13].

Depicted in two-dimensional form, the pressure coefficient, lift, and drag is non-dimensional coefficients. It can be written based on freestream dynamic pressure, $q\infty$, and chord (c)[1] as

$$C_L = \frac{L}{q_\infty c}, \quad (9)$$

$$C_D = \frac{D}{q_\infty c}, \quad (10)$$

$$C_M = \frac{M}{q_\infty c}. \quad (11)$$

In aircraft design, central stabilization needs to withstand the aircraft's pitching movement or keep its fuselage in a horizontal condition. T-tail is considered one of the best empennage matrix forms [9].

In designing an empennage, we need a simple chord reference from the main wings as [9]:

$$MGC = \left(\frac{2}{3}\right)C_R\left(\frac{1+\lambda+\lambda^2}{1+0.5}\right) \quad (12)$$

Then we get the geometry empennage with [9]:

$$L_T = \sqrt{\frac{2S_{ref}(V_{HT}C_{ref})(V_{VT}b_{ref})}{\pi(R_1+R_2)}} \quad (13)$$

Horizontal Tail :

$$S_{HT} = \frac{V_{HT}C_{ref}S_{ref}}{L_T}, \quad (14)$$

$$b_{HT} = \sqrt{AR_{HT}xS_{HT}}, \quad (15)$$

$$C_{avgHT} = \frac{B^2}{S} = \frac{B}{AR}, \quad (16)$$

$$C_{RHT} = \frac{2C_{avg}}{(1+\lambda)}, \quad (17)$$

$$C_{THT} = \lambda xC_R. \quad (18)$$

Vertical Tail :

$$S_{VT} = \frac{V_{VT}C_{ref}S_{ref}}{L_T}, \quad (19)$$

$$b_{VT} = \sqrt{AR_{HT}xS_{HT}}, \quad (20)$$

$$C_{avgVT} = \frac{B^2}{S} = \frac{B}{AR}, \quad (21)$$

$$C_{RVT} = \frac{2C_{avg}}{(1+\lambda)}, \quad (22)$$

$$C_{TVT} = \lambda xC_R. \quad (23)$$

II. RESEARCH METHOD

The research was carried out in several stages, starting with a literature review to produce a design concept through the design analysis process. Then, technical data from various related references [4], [6-7], [11-12], [15] is used as a linear regression to obtain trends and characteristics of similar sailplanes. At this stage, the wing area's value, aspect ratio, empty weight, and wing loading from the average length of the overall fuselage are obtained, as shown in Figs. 5 – 8.

According to the numerical data, FX 66-17AII-182 airfoil for main wings was selected because it had a high Cl value at an angle of 130, a high (Cl / Cd) value of max height, and a high stall angle. Meanwhile, for airfoil empennage, NACA 0009 was used as airfoil data obtained from the UIUU Catalog [8], [14]. This data is then re-validated with the help of XFRL5 software and comparison with relevant research [3], [16].

To perform airfoil analyses, we employed XFLR5 software with the XFOIL algorithm. This software is capable of making 2D infinite wing and 3D finite wing analyses. In this way, the full wing, the selected wing profile, and the full wing L/D ratio are analyzed. We obtain a 0.355 m wing profile from the regression equation, whereas the aspect ratio is 22.44 when the wing area is 10.03 m^2. The Reynolds number [1]:

$$Re = \frac{Vc}{v}. \quad (24)$$

In this case, the Reynolds number at constant flight speed is expected to be between 200,000–300,000. It is obvious that Reynolds numbers at different altitudes, speeds, and other parts of the wing will be different. Therefore, we determine the measurement range at 50,000 and 500,000 in which the analysis is performed at this range.
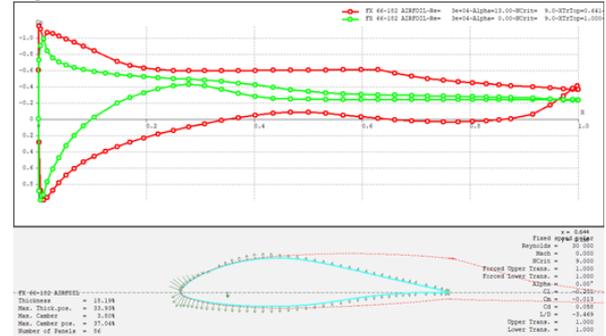
Fig. 4. 2D analysis of FX 66-182 in XFLR5.

The FX 66–182 airfoil, optimized by Wortmann with a profile drag coefficient of 0.0055, was chosen as the design profile. This profile shows a maximum 85,650 l/d ratio at 4° in 200,000 Reynolds (see Fig. 4).

L/D max ratio represents pure flight performance and equals the maximum glide ratio. The maximum glide ratio at the minimum glide angle can be easily obtained (Kafali and Keskin, 2020).

Geometry modeling using CAD software [5] obtained a sailplane scale mass of 429 kilograms. The simulation process [2] used a tool to perform calculations with the RANS (k-ε) turbulent flow model approach with variations in the speed of 90 km/h and 165 km/h to obtain the characteristic of air around the sailplane [10].

A. Design Requirement & Objective (DR&O) Reference Data

The research begins with planning the general objectives of the sailplane, which is presented in Table II.

TABLE II
DR&O REFERENCE DATA

Parameter	Description / Value
Geometry Aspects	
Wingspan	15m
Configuration Aspects	
Wing Position	Mid-Wing
Tail Configuration (Empennage)	T-Tail
Aspects of Achievement and Stability	

Stall speed & Cruise speed	≤ 20 m/s (72 km/h) & ≤ 55 m/s (198 km/h)
Minimum sink speed	≤ 20 m/s (72 km/h)
Glide Ratio	≥ 20
Structural Aspects	
The main material	Steel-tube center section framework, fiberglass sandwich fuselage PVC foam core wings with a fiberglass skin.
Special Specifications	
Payload	One passenger's time is 175 lbs (70 kg) and 60 lbs (27 kg) for luggage.

Cruise speed	100 Knots ; 185.185 km/h ; 51.44 m/s
Certification Base	FAR 23; JAR 22

B. Comparative Aircraft Study

In the sailplane technical data collection process, we obtain data from companies, related studies, and various associated references [4–9].

The data presented in Table III are used as linear regression parameters to obtain trends and characteristics of a similar sailplane. The wing area, aspect ratio, empty weight, and wing loading values of the overall fuselage's average length are obtained from this stage, as shown in Fig. 5.

TABLE III
DATA SHEET GLIDER SCHEMPP-HIRTH FACTORY

Parameter	Type Glider						
	Cirrus	Ventus	Discus-2a	Discus-2b	Discus-2cFES	Discus-2c	Discus-2cT
Fuselage Length, f(m)	6.41	6.76	6.81	6.78	6.78	6.78	6.76
Wing Area, S(m2)	10.16	9.53	10.16	10.16	10.16	10.16	10.16
Wing Loading (kg/m^2)	41.2	41	41.2	45.5	42.95	44.2	41
Max.Flying Mass (kg)	525	525	525	525	525	525	525
Aspect Ratio	22.2	23.6	22.2	22.2	22.2	22.2	23.6
Empty Mass (kg)	242	300	252	30	270	320	300
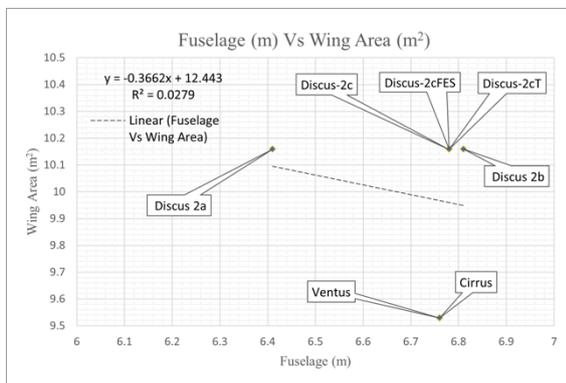
(a)
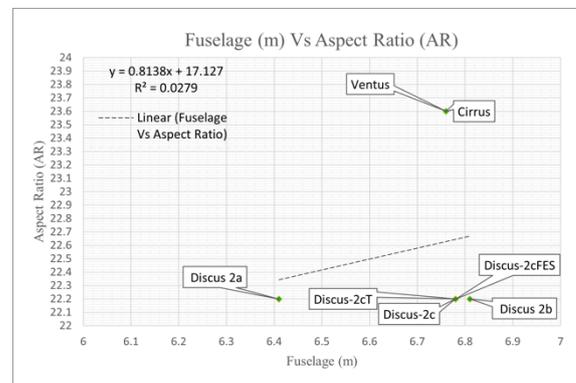
(b)
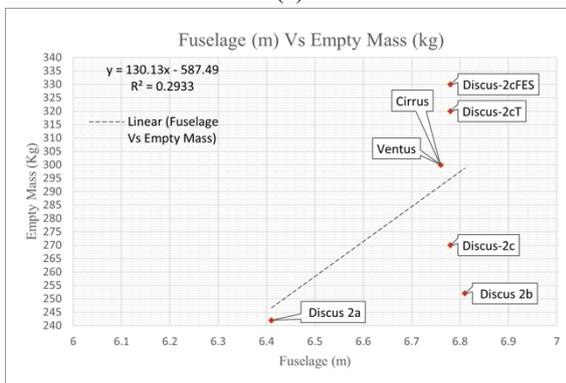
(c)
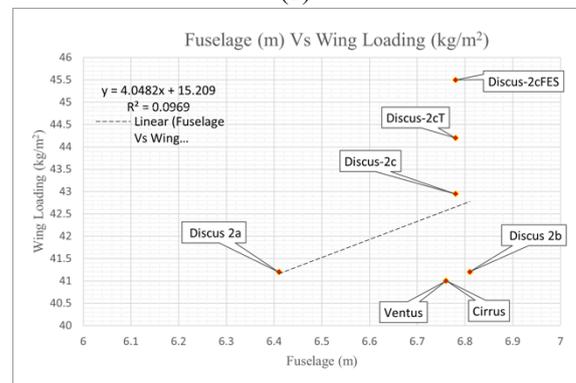
(d)

Fig. 5. Regression approach (a) fuselage vs wing area (b) fuselage vs aspect ratio (c) fuselage vs empty mass (d) fuselage vs wing loading.

By using the regression equation in Fig. 6, with the average fuselage length obtained from Table III (6.73 meters), we obtain the initial data as follows.

1. Sailplane Body Geometry (Fuselage)

TABLE IV
GLIDER GEOMETRY DATA REGRESSION APPROACH

Description	Value
Fuselage	6,74
Wing Area (m^2)	10,03
Aspect Ratio	22,44
Empty Mass (Kg)	286,90
Wing Loading (Kg/m^2)	42,72
Wingspan (m)	15

From the comparative aircraft data, the fuselage's length to be made is 6.73 meters, which according to the standard for cockpit dimensions, the height was 1.20 meters, and the width was 0.90 meters [9]. The sailplane design is divided into seven segments, where the first segment has a parabolic shape, and the rest is a frustum. Then the fuselage geometry is obtained using (1)-(6).
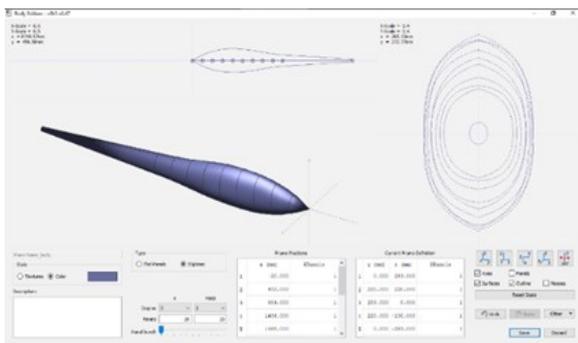
Fig. 6. Design fuselage using XRLF5.

2. Main Wings Geometry

The wings' geometry is made by referring to reference data (Table III) and using equations (5), (6), and (13). As a result, the primary wing geometry is obtained as follows.

TABLE V
GEOMETRY FUSELAGE SAILPLANE

Description	Value
Fuselage Diameter (Cm)	64 – 120
Segment Range (Cm)	0.502
Surface Area (Cm^2)	22,44
Volume (Cm^3)	286,90
Chord Root (m)	0.8912
Chord Tip (m)	0.4456
MGC (m)	0.3466

3. Empennage Geometry

For the stability of the sailplane, empennage geometry was built using T-tail based on the main wing parameters, which are substituted into equations (12)-(23). We obtain the empennage geometry data as follows.
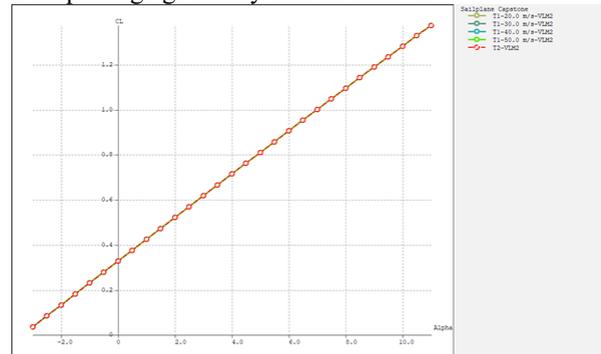
Fig. 7. Coefficient of lift vs angle-of-attack.

TABLE VI
EMPENNAGE GEOMETRY SAILPLANE

Parameters	Description	
	Vertical Tail	Horizontal Tail
Area, S (m2)	0.514	1.543
Span, b (m)	1.242	2.7778
*Aspect ratio, AR	5	3
*Taper ratio, λ	0.5	0.5
Chord Root	0.552	0.741
Chord Tip	0.276	0.370

III. RESULTS AND DISCUSSION

According to the results of numerical studies, the sailplane geometry is obtained as follows.

A. Aerodynamic Data

The parameters used in the analysis process include the total weight data obtained using the material density approach used in the design, which is 429 kg. The data is obtained with the position of the center of gravity at the coordinates X_CoG = 48.032 cm, Y_CoG = 0 cm, and Z_CoG = 7,730 cm from the position of the datum right at the leading edge of the wing. After analyzing with CFD software and calculating the drag polar from the designed glider, the result is obtained.

In Fig. 8, we present the coefficient of drag vs angle-of-attack result. The red line on the graph is the polar of the fixed lift analysis, where the equivalent lift at each angle of attack has the same value. Note that in Fig. 8, the angle of attack 20 has a high coefficient lift/coefficient drag.
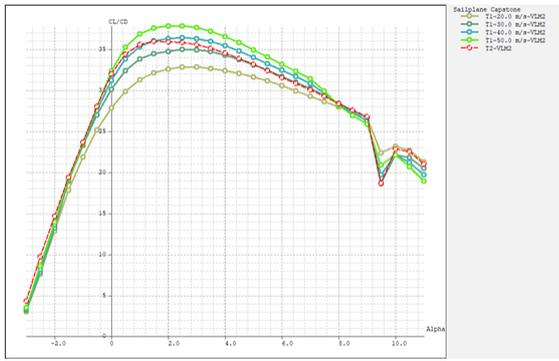
Fig. 8. Coefficient of drag vs angle-of-attack.

The variations of speed have a uniform coefficient of lift versus coefficient of drag graph but have different coefficient values at each speed. Fig. 9 is a graph of each simulation's velocity. The red graph in the simulation is intended to obtain the value of the speed at the same lift as the normal force of the FG-S sailplane and on the other four graphs with a constant velocity of the angle of attack given. In Fig. 9, the speed is set as 20 m/s, and the sailplane is below the lift (stall) value. As shown at an angle of 0^0 (degrees), the minimum speed required for a hovering sailplane is 50 m/s. At a speed of 40 m/s, the angle-of-attack needed for a hovering sailplane is 1.5^0 (degrees), while at a speed of 30 m/s, the minimum angle of attack for a sailplane to fly is 5.5^0 (degrees).
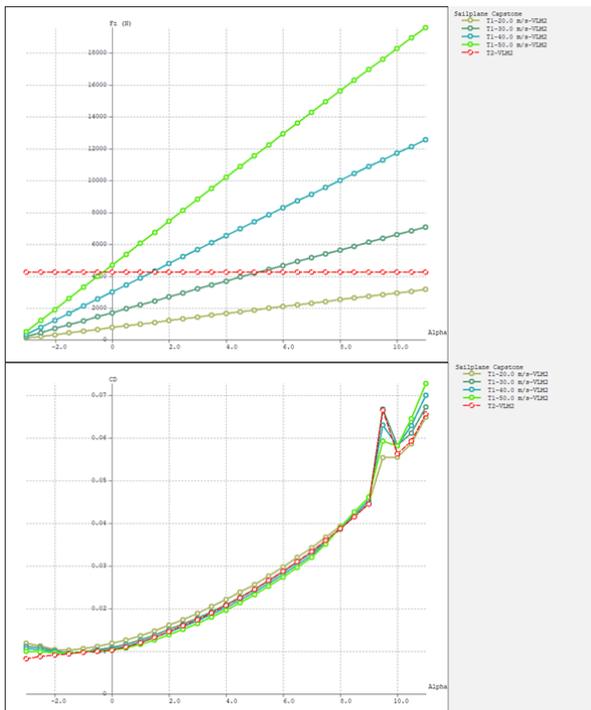
Fig. 9. Graph of the velocity of simulations in Fig. 7 (top) and Fig. 8 (bottom).

B. Turbulent Kinetic Energy

ANSYS software is used as a visualization tool, whereas XRLF5 software is used as an evaluation tool of the performance parameters in analyzing flight performance and stability. Several parameters were inputted in the analysis process. The total weight data obtained using the material density approach used in the design was 429 kg,

including additional components. The following result is a summary of the flight performance data from the design gliders.
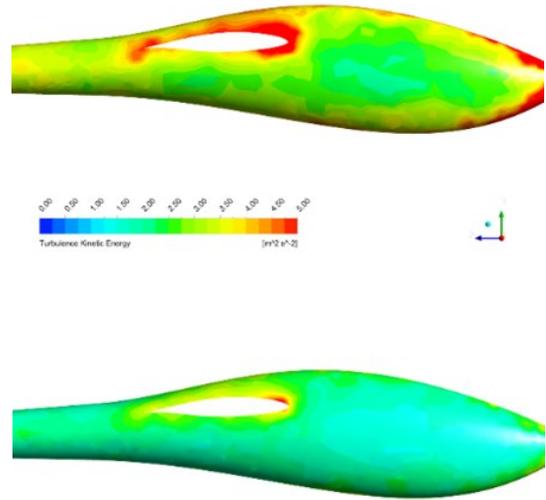
Fig. 10. The turbulent kinetic energy at fuselage speeds 90 km/h (top) and fuselage speed 165 km/h (bottom).

In Fig. 10, we can see the production of turbulent kinetic energy on the side of the standard cirrus. The transition model can predict the transition from laminar to turbulent airflow on both the wings and the glider's fuselage. On the left of the figure is the freestream simulation velocity at 95 km/h.
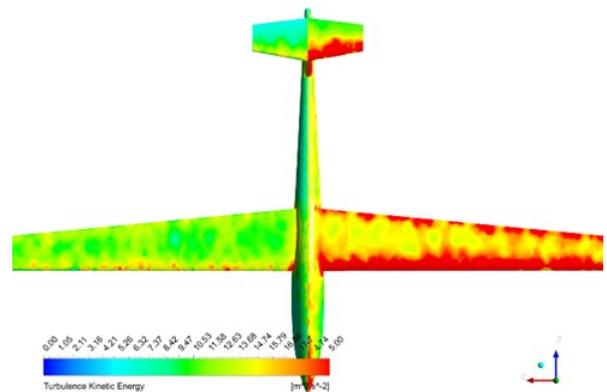
Fig. 11. The turbulent kinetic energy at the upper fuselage speeds 90 km/h at the bottom at a speed of 165 km/h.

Fig. 11 shows the production of turbulent kinetic energy on the top side of the standard cirrus. The transition model in Fig. 11 can predict the transition from laminar to turbulent airflow on both the wings and the glider's fuselage with a freestream simulation at a velocity of 95 km/h. At this velocity, the transition process starts approximately at the mid-chord along the span of the wing. The laminar separation bubble displays the region where turbulent kinetic energy production is the highest. Behind the laminar separation bubble is the reattachment region.

The figure on the right side is a 160 km/h simulation.
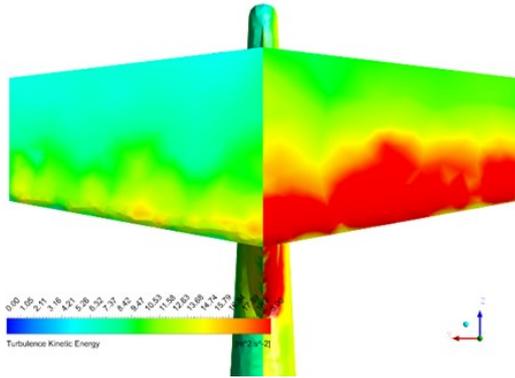
Fig. 12. Turbulent kinetic energy at the upper empennage: the left part is at 90 km/h, the right part is at 165 km/h; the lower part of the right speed is 90 km/h, the lower part of the left is at a speed of 165 km/h.
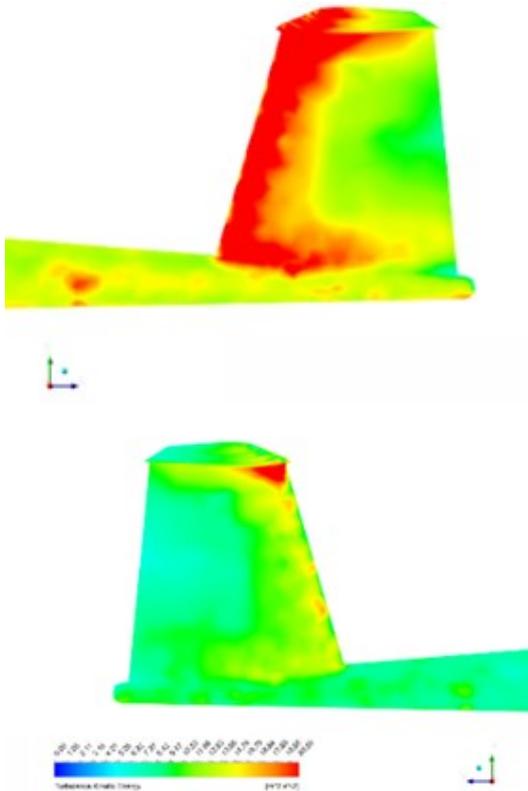
Fig. 13. Vertical empennage: on the right part is at a speed of 90 km/h (bottom) and on the left is at a speed of 165 km/h (top).

In Fig. 12, we can see the production of turbulent kinetic energy on the top of the elevator section. The results followed the trends from the simulations performed for the wings of the glider. The 95 km/h simulation on the left side in the figure has a low production of turbulent kinetic energy making the laminar separation bubble small. The transition for the 165 km/h simulation on the right part is moving forward, and turbulent kinetic energy production has increased. Also, on the elevator surface, large regions of laminar flow exist at the tips (see Fig. 13).

A. *Performance Flight Glider*

The performance of the sailplane was analyzed using the XFLR5 software with the parameter value as follows.

Parameter	Value
Stall Speed	
AoA = 0^0	≤ 49.5 m/s
Glide Ratio (L/D)	
Cruise Speed = 20 m/s	16.54
Cruise Speed ≥ 20 m/s	≥ 20
Cruise speed = 30 m/s	25.05
Lift	
Vmin $0^0 =$ 49.5 m/s	6023 N

IV. CONCLUSION

A rapid preliminary design with the regression method of flight data is useful for designing new sailplane designs. In this article, we successfully obtained the geometry and configuration data of the scale model glider sailplane. By using the regression method, a rapid preliminary sailplane design was performed. The sailplane's aerodynamic characteristics of the proposed model indicate that the distribution of pressure coefficient, lift coefficient, and drag polar is in accordance with DR & O requirements.

In general, the aerodynamic aspects of the sailplane are relatively good. At a speed of 20 m/s, the sailplane is below the value of lift (stall). Fig. 9 shows a graph (lift at various angles) at an angle of 0^0 (degrees). The minimum speed required for a hovering sailplane is a speed of 50 m/s. At a speed of 40 m/s, the angle of attack needed for a hovering sailplane is 1.5^0 (degrees), while at a speed of 30 m/s, the minimum angle of attack for a sailplane to fly is 5.5^0 (degrees). The turbulent transitions at each velocity at an angle of 0^0 have almost a uniform contour. Some flight movement modes, such as the yaw, can handle the pilot's role in using control surfaces.

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Mohamad Yamin is the Head of Center for Automotive Research at Gunadarma University, Jakarta, Indonesia. His undergraduate degree is in Aeronautics from ITB University, Bandung, Indonesia (1993), and his doctorate (2003) is in Aerodynamics, ILR, TU-Berlin, Germany. His research interests are CFD, Aerodynamics, Dynamics & Control, EV, and Machine learning. (email: mohay@staff.gunadarma.ac.id)

Ahmad Fakhri Giyats was born in Jakarta, Indonesia, in 1999. He received the B.S in mechanical engineering from Gunadarma University, Indonesia in 2021. In 2022 he received the master's degree in mechanical engineering from Gunadarma University. He was a Research Assistant with the Center for Automotive Research Laboratory. Since 2021 he is a Research fellow in Mechanical Engineering Department, Gunadarma University, Indonesia. His research interest includes fluids mechanic and applied artificial intelligence. (email: afgiyats@gmail.com)