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Research paper

The Development of Student Station for Drag Polar Testing

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Abstract

In order to improve the teaching and learning activities in the flight mechanic subjects, the Aerospace Engineering Program, ITB, is currently developing a flying laboratory, based on a fixed-wing unmanned aerial vehicle (UAV). The development process itself has reached a phase, where both graphical user interface (GUI) and flight testing scenario for drag polar assessment are being developed, and evaluated. The evaluation of the GUI is performed by creating a simulated flight testing using X-plane software. Due to the model availability in the X-plane, a Cessna 172 model is used instead of a fixed-wing UAV model. The drag polar test is conducted by trimming the aircraft model in steady symmetric level flight condition using the autopilot provided by X-plane. In the simulated test scenario, the aircraft weights and trim speeds are varied while the altitude and and center of gravity (CG) location are held constant. The flight data is then captured and processed with the developed GUI. Further, the lift coefficient (C_L) and drag coefficient (C_D) are obtained from the aircraft weight, engine thrust, trim speed, and the corresponding atmospheric data. The coefficients are plotted and a curve fitting process is performed to obtain the analytical approximation of the drag polar curve. When the calculation results are compared to the lift and drag coefficients data of the aircraft model, obtained directly from X-plane software, both of them are in a good agreement. Differences might appear from the incompatibility in the drag components calculation of the X-plane software.

Keywords: *Drag Polar; Flight Testing; Flying Laboratory; UAV*

1. Introduction

Aerospace Engineering Program at Institut Teknologi Bandung (ITB) is currently developing a fixed-wing Unmanned Aerial Vehicle (UAV) to be used as a flying laboratory. The UAV is equipped with sensor, autopilot, data acquisition, data recording, and data telemetry systems. It is also equipped with a ground control station that receives, displays, and records the flight data. This laboratory will be used as part of the teaching process in the Aerospace Engineering Program, specifically in the flight mechanics subjects. By utilizing this laboratory, students can be involved in conducting static stability test, drag polar test, and dynamic stability test.

In the previous works [1][2], a graphical user interface (GUI) for longitudinal static stability assessment has been developed. Continuing the previous work, this paper will specifically discuss about the development of a GUI and test method for drag polar assessment.

The drag polar characteristic of an aircraft can be obtained through a certain flight test method. Reference [3] and [4], describe a flight test method for a fixed-wing aircraft. However, the presented method needs to be adjusted for used with UAVs. For example, the flight testing in UAVs require autopilot to be used to maneuver and trim the aircraft. Another example is that in an electric powered UAV, the weight of the UAV does not decrease over time as most manned aircraft do, due to the fuel burning. A small UAV also has a limited speed range, such that the drag polar data that can be obtained will also be limited in the lift coefficient range.

In reference [5], it is explained how to obtain drag polar characteristic of a UAV by using the descent method. This method is conducted to determine the flap effects on drag. Another work [6] presents a flight test method to obtain the performance characteristic of a small electric powered UAV. The electric-powered UAV is flown in a steady symmetric level flight condition, and the airspeed, current, and voltage of the UAV are measured in order to calculate coefficient of lift (C_L) and drag coefficient (C_D). Since the UAV used has a fairly wide range of speed, the flight test is conducted only by varying the flight test speed to cover a good range of lift coefficients.

In this work, a similar flight test method to [6] will be used. In order to increase the number of drag polar data that can be obtained to sufficiently cover the lift coefficient range, in addition to the airspeed variation, the weight of the UAV will be varied without changing the location of the center of gravity (CG).

The developed GUI will allows the users to monitor, record, and process all of the flight test data to find the drag polar characteristics of the UAV.

Before the developed GUI can be used in the real flight test, it is needed to be validated first. A flight test simulation using X-Plane software is conducted in order to validate the developed GUI. The GUI program is connected to the X-Plane and receive the flight test simulation data from the software. The drag polar characteristics of the result of the GUI data processing will be compared with the drag polar characteristics of the aircraft model in the X-Plane software.

2. Determination Drag Polar

The drag polar is a chart presenting the relationship between aircraft's lift and its drag, expressed in terms of the dependence of the drag coefficient on the lift coefficient. By using its drag polar data, the other aircraft's performance parameters can be determined and evaluated. The general form of the drag polar can be expressed in the parabolic equation as follows:

$$C_D = C_{D0} + KC_L^2 \quad (1)$$

where C_D is coefficient of drag, C_{D0} is zero lift drag coefficient, K is induced drag constant, and C_L is coefficient of lift.
Alternatifely, it can be written in quadratic equation as follows:

$$C_D = C_{D0} + K_1C_L + K_2C_L^2 \quad (2)$$

where K_2 and K_1 are constant. Parabolic equation (1) assumes that the minimum drag occurs at zero lift. So, the drag polar is centered on the drag axis.
In order to construct the drag polar, C_D and C_L must be obtained for various flight conditions. In steady symmetric flight condition, the forces and moment acting of the aircraft are in the equilibrium condition, represented by the followings:

$$\sum F_y = 0 \quad (3)$$

$$W = L \quad (4)$$

and

$$\sum F_x = 0 \quad (5)$$

$$D = T_r \quad (6)$$

where

$$L = 0.5\ \rho V^2SC_L \quad (7)$$

$$D = 0.5\ \rho V^2SC_D \quad (8)$$

where W is the aircraft weight, L represents lift, T_r represents the thrust required, D is drag, V is airspeed, S is wing area, and ρ represents the air density.
Hence, we can combine Equation (4) and (7) to obtain the lift coefficient and combine Equation (6) and (8) to obtain the drag coefficient. The results are as follows:

$$C_L = \frac{2W}{\rho V^2 S} \quad (9)$$

$$C_D = \frac{2T_r}{\rho V^2 S} \quad (10)$$

By multiplying both sides of Equation (6) with airspeed, the power required can be obtained as follows:

$$T_rV = DV \quad (11)$$

$$P_r = T_rV = 0.5\ \rho V^3SC_D \quad (12)$$

If the engine's total efficiency (η) is known, then the relationship between mechanical power required for flight (P_r) and the electrical power available supplied to the electrical engine (P_e) can be written by the following equation :

$$P_r = \eta P_e \quad (13)$$

Since the electrical power can be defined as the product of the voltage (E) and the current (i) into the electrical motor, so the C_D can be calculated by using this equation :

$$P_e = iE \quad (14)$$

$$C_D = \frac{2iE\eta}{\rho V^3 S} \quad (15)$$

By obtaining the value of C_L and its following C_D as many as possible, a diagram called a polar plot can be drawn. By fitting the obtained data with a second order polynomial, the remaining parameters in the quadratic drag polar equation such as C_{D0}, K_1, and K_2 can be determined. In the case of parabolic equation, the constant K and C_{D0} can be determined by plotting C_D vs C_L^2 as follows:

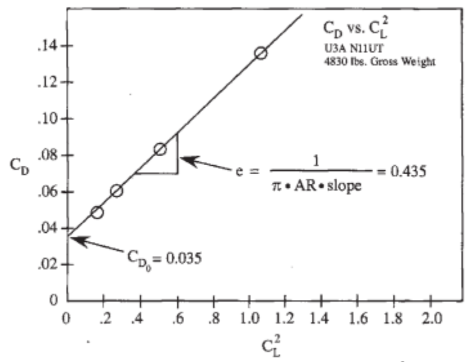

Fig. 1: Example plot of C_D vs C_L^2 [4]

3. Propeller Efficiency Data

In order to obtain the drag polar characteristic of a UAV, the thrust data during flight test is needed. However, it is difficult to measure the thrust data directly from the propeller. Therefore, the propeller thrust is determined beforehand by conducting a thrust measurement in a wind tunnel. By conducting a wind tunnel test, the data of the propulsion system of the UAV, such as electrical current, voltage, propeller rotational speed, total efficiency of motor-propeller combination, and thrust, can be determined over the range of possible throttle settings and vehicle velocities. Thus, the thrust data does not need to be measured directly during the flight test, but be inferred from other data, such as electrical current, voltage, and vehicle velocities. Then, efficiency data will be obtained according to the following:

$$\eta = \frac{P_{out}}{P_e} = \frac{TV}{iE} \quad (16)$$

Efficiency and thrust data is incorporated the database of the GUI program.
In this work, the propeller thrust is obtained directly from the X-Plane output. However, the developed GUI, is prepared with an interpolation function to process the propeller thrust data from wind tunnel testing.
Other data that must be calculated before the flight test are the total weight and the center of gravity of the aircraft. Wing area data and equation for calculating air density have been included in the GUI program.

4. Drag Polar Test Method

The parameters that are still needed to calculate C_L and C_D from equation (9) and (15) are airspeed, current, and voltage of UAV's electric motor. These parameters are measured when the UAV has been flown in a trim condition. The trim condition is indicated by airspeed, altitude, elevator deflection, and pitch angle that are not vary in time. During each trim condition, some data, such as time, airspeed, elevator deflection, altitude, pitch angle, current, voltage, total thrust, and total efficiency are recorded. For each trim condi-

tion, a single data of drag polar will be created. So, multiple point can be plotted by varying the airspeed.
Since, the speed range of the UAV is short, the users will only get a few airspeed variations. In order to get more drag polar data, the mass of the UAV must be varied as well during the flight test. The UAV flight data transfer is illustrated in the Figure 2.

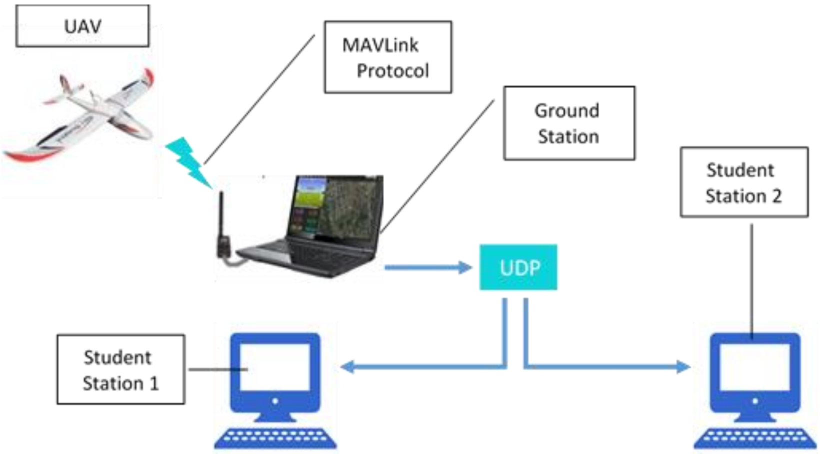

Fig. 2: Data transfer from flight testing UAV [7,8]

As shown in Figure 2, the UAV is equipped with some sensor systems, such as altitude, airspeed, current, voltage, and pitch angle sensor. Through the MAVLink Protocol, the flight data will be received by a ground station computer. In the ground station computer, the data is processed. After that, using User Datagram Protocol (UDP), data is transmitted to the student station where a GUI is installed in a computer. Therefore, the users can monitor, record, and analyze the flight data.

5. GUI Design for Student Station

Based on the drag polar test method described above, a GUI has been designed. The interface was built using Matlab 2017a and connected via UDP. The GUI consists three windows. The main window (Figure 3) displays the flight data in real-time, data input, and buttons command to take the data. The data that has been taken is then saved and displayed in the second window (Figure 4). The stored data can be loaded and used to estimate the drag polar characteristic (Figure 5).

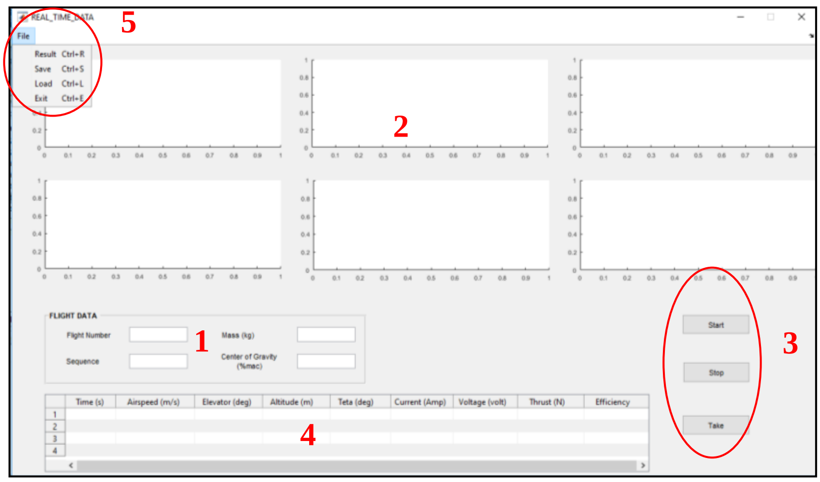

Fig. 3: The main display of the GUI program

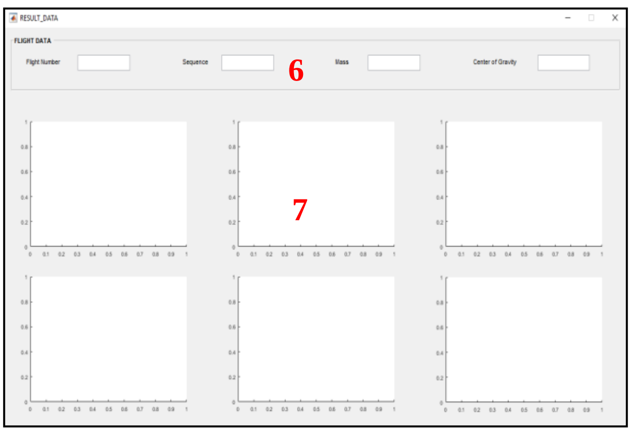

Fig. 4: The second display or window of the GUI program

Fig. 5: The third display or window of the GUI program

In Figure 3, the main display of the GUI is shown. It can be seen that there are several parts in the main display, marked by number one through number five. The part marked by the number one, named ‘Flight Data’, is the part where the users can input flight number, sequence, mass, and CG location of the UAV. In the part number two, there are six charts that display the UAV’s flight data in real-time. The data shown on the graph include data on airspeed, altitude, elevator deflection, pitch angle, current and voltage of the UAV’s electric motor. The first and the second buttons marked by number three, are the buttons to start and to stop the real-time flight data plotted in the charts which have been explained previously. The last button is used to take the flight data when the UAV has been flown in a steady symmetric level flight condition. In the part marked by number four, the trim data captured by the users are displayed, such as time, airspeed, elevator deflection, altitude, pitch angle, current and voltage of UAV’s electric motor, total thrust, and total efficiency of UAV’s motor data. The data of total thrust and total efficiency of the UAV’s electric motor are obtained from wind tunnel testing, while another data are obtained from the flight test. Part number five represents some menu, they are ‘Result’, ‘Save’, ‘Load’, and ‘Exit’. The ‘Result’ menu is used to display the GUI shown in the Figure 4, while the ‘Load’ menu is used to display the GUI shown in the Figure 5. In order to save the numerical data obtained during the test flight, the ‘Save’ menu can be used. The last menu, ‘Exit’, can be used when the user has finished using the GUI.
The second window of the GUI is shown by Figure 4. There are two parts in this window, first part, marked by number six, displays the data of flight number, sequence, mass, and CG location, and second part, marked by number seven, displays the trim data in graphical form, including elevator deflection against airspeed, thrust against airspeed, pitch angle against airspeed, flight path angle against airspeed, angle of attack against airspeed, C_L against angle of attack, and C_D against angle of attack.
The last window of the GUI is shown in Figure 5. Just like the previous window, the third window consists of two parts, marked by number eight and nine. Number eight marks the part that displays graphic and numerical data from C_L and C_D. The data will appear after the users press the ‘Load’ button. Number nine marks the part that displays the drag polar characteristic, both in quadratic and parabolic equation. The data will appear after the users press the ‘Drag Polar’ Button.

6. Simulation Scenario

To demonstrate the ability of the GUI program, a flight test simulation has been performed using X-Plane 11 software. Because X-Plane does not provide a UAV model, Cessna 172S model is used in the simulation. Since a simulation is used to subtitute the real flight test, MAVLink Protocol is then replaced by UDP, and ground station computer is replaced by Simulink, as shown in the following figure:

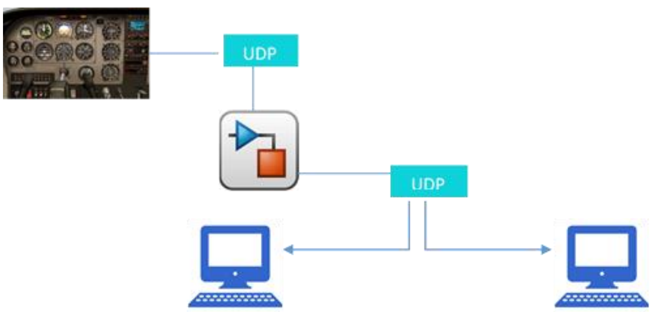

Fig. 6: Data transfer from flight testing simulation [9]

The flight simulation is conducted in the following scenarios in Table 1.

Table 1: Flight test simulation scenarios using Cessna 172S in X-Plane 11

Flight Number	Total Weight	Airspeed	Flight Condition
1	1000 (kg)	67 m/s 60 m/s 50 m/s	- Cruise flight - Altitude 915 m - Flap fully retracted - Center of gravity location 0 by default X-Plane
2	802 (kg)	67 m/s 60 m/s 50 m/s 42 m/s	
3	902 (kg)	66 m/s 60 m/s 51 m/s	

In the simulation, there are some adjustments used on the aircraft data. The current and voltage data of the UAV’s electric motor that should be a GUI database obtained from wind tunnel testing are replaced by calculation data using the following relation :

$$iE = TV/\eta \quad (17)$$

where T, V, and η as the input from X-Plane data and iE as the output data in GUI during simulation.

7. Result and Discussion

In this section, the GUI’s ability to display, record, and process the obtained data during the flight testing is discussed. In addition, the simulation results data displayed by the GUI will be validated using the results data obtained from X-Plane.

7.1 Flight Simulation Data

A flight test simulation has been conducted three times, each with different aircraft mass. All of the flight data have been displayed, recorded, and processed using the GUI program. In order to show the display of the GUI while processing the flight data, a screenshot of the main display is presented in Figure 7.

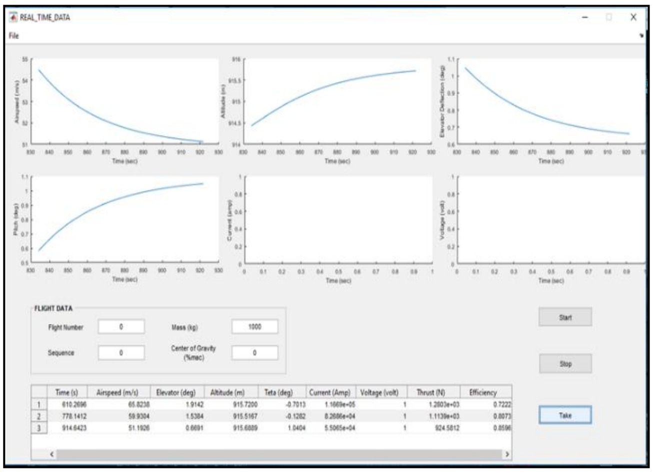

Fig. 7: The main display of the GUI displays the flight data of the flight simulation number one

The figure above shows that the GUI can receive the flight data, display the data in real-time, and take some data when the aircraft was in a trim condition. The graph plotted from the real-time data helps users to identify whether the aircraft has been in a trim condition or not, so the users can decide a right time to take the trim data. When the aircraft has reached the trim condition, the real-time graph of altitude, velocity, elevator deflection, and pitch angle will not vary in time. Figure 7 shows that the aircraft almost reach its trim condition, indicated by a convergent curve at a certain value.

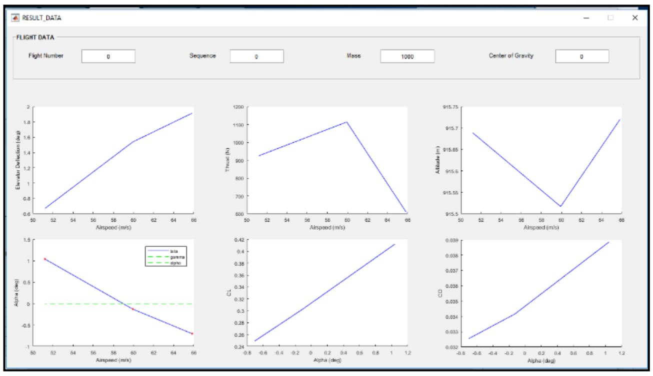

Fig. 8: The second window of the GUI displays the trim data of the flight simulation number one

After several trim data were taken in several trim conditions, the users can use the 'Result' menu in the main display to see all of the obtained data. As described before, after the 'Result' menu was choosen, the second window of the GUI will appear and displays the trim data. Figure 8 shows the screenshot of the second window when displaying the trim data of the flight simulation number one. There are six graph in the window as described in the chapter five before. The flight path angle or gamma in the graph is calculated by using the following equation

$$\gamma = sin^{-1}\left(\frac{\dot{h}}{V}\right) \qquad (18)$$

where $\dot{h}$ is the rate of climb.

The figure in the left side shows that the GUI can process the trim data that were taken before and displays it in a graphical form. The program not only can display the trim data in a graphical form, but also in a numerical form as presented in the Table 2 below.

Table 2: The trim data of the flight simulation number one

Flight Number = 1
Sequence = 0
Center of Gravity = 0.000
Mass = 1000.000

--------------------Flight Test Data--------------------

Time	Airspeed	Elevator	Altitude	Teta	Gamma	Alpha	Current	Voltage	Thrust	Efficiency
610.270	65.824	1.914	915.720	-0.701	-0.001	-0.700	116688.559	1.000	1280.344	0.722
778.141	59.930	1.538	915.517	-0.128	-0.001	-0.127	82685.817	1.000	1113.888	0.807
914.642	51.193	0.669	915.689	1.040	-0.001	1.042	55065.028	1.000	924.581	0.860

CL	CD
0.249295	0.032548
0.300730	0.034158
0.412159	0.038859

By using the graphs, the users can define the static stability and the aerodynamic characteristic of the aircraft easily. For example, the users can analyze the graph of angle of attack against airspeed. In order to show a statically stable manner, the curve on the graph must have a negatif gradient, or in other words, if the airspeed of the aircraft increases, the angle of attack of the aircraft should be decreases in a certain pattern. The graph can also be used to see wheter the data has been taken in a trim condition or not. Since almost all aircraft is designed to be statically stable, so, in a trim condition the angle of attack of the aircraft should be decreases if the airspeed is increased. In the other hand, the numerical form of the trim data will help the users to analyze the characteristic of the aircraft in more detail.

7.2 Drag Polar

In order to analyze the drag polar characteristic of the aircraft, the users can use the 'Load' menu in the main display to bring out the third window of the GUI. Figure 9 displays the drag polar data of Cessna 172S as the result of the GUI program calculation. Different colors of the points show the different mass of the aircraft used in the flight simulation. The distribution of the points indicates that if the mass variations used in the flight test is increased, it will produce more data for drag polar analysis.

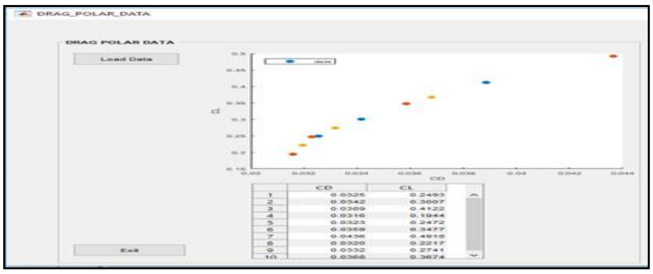

Fig. 9: Drag polar data obtained from the flight simulations

The GUI also displays first and second order polynomial curve fitting, so the users can find the coefficients of the drag polar equation (Equation (1) and Equation (2)) easily. In order to find the coefficients of Equation (2), second order polynomial curve fitting is used. In the other hand, first order polynomial curve fitting is used to determine the value of the coefficients of Equation (1).

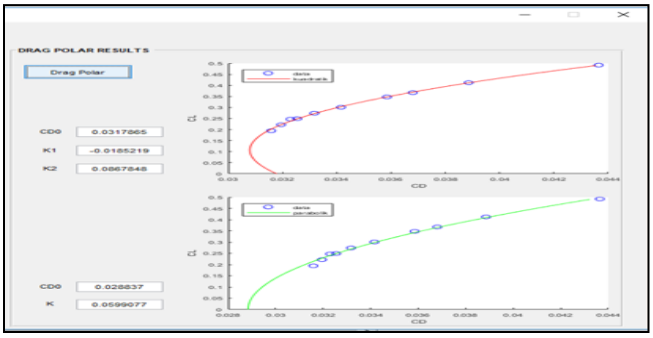

Fig.10: Curve fitting in order to find the coefficients of the aircraft's drag polar characteristic

From the drag polar results shown in the Figure 10, on the graph at the top, it can be found that the value of C_{D0} is 0.03179, K_2 is 0.08678, and K_1 is -0.01852, which results the following quadratic drag polar equation :

$$C_D = 0.03179 - 0.01852\ C_L + 0.08678\ C_L^{\ 2} \qquad (18)$$

From the same figure, on the graph at the bottom, the value of C_{D0} was found to be 0.02884 and the value of K was found to be 0.05991, which gives following parabolic drag polar equation:

$$C_D = 0.02884 + 0.05991\ C_L^{\ 2} \qquad (19)$$

C_L and C_D data as the results of the GUI calculation are then compared with C_L and C_D data obtained from X-Plane software. The result of C_L/C_D ratio from GUI and C_L/C_D ratio from X-Plane are shown in the tables below:

Table 3: C_L and C_D from GUI calculation

No	C_D	C_L	C_L / C_D
1	0.03255	0.24929	8
2	0.03416	0.30073	9
3	0.03886	0.41216	11
4	0.03159	0.19441	6
5	0.03229	0.24722	8
6	0.03585	0.34769	10
7	0.04365	0.49181	11
8	0.03195	0.22172	7
9	0.03318	0.27408	8
10	0.03680	0.36735	10

Table 4: CL and CD from X-Plane Output Data

No	C_D	C_L	C_L / C_D
1	0.02796	0.22850	8
2	0.02949	0.27370	9
3	0.03384	0.37352	11
4	0.02667	0.17879	7
5	0.02789	0.22546	8
6	0.03112	0.31559	10
7	0.03788	0.44471	12
8	0.02726	0.20326	7
9	0.02865	0.24976	9
10	0.03191	0.33336	10

Since X-Plane is a software developed for manned aircraft simulation, it will simulate the fuel flow of the aircraft, so the mass and the CG location of the aircraft that is simulated in X-plane will be change over time. In the other hand, the calculation method used in the GUI was designed for UAV and does not calculate the fuel flow. This difference cause the results of C_L and C_D between the two are slightly different, as shown in the Figure 11.

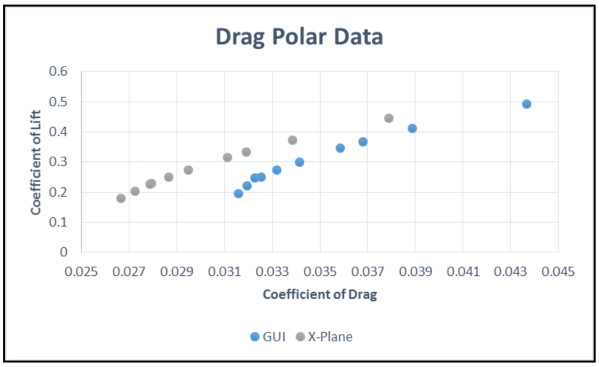

Fig. 11: C_L and C_D from GUI and X-Plane

8. Conclusion

A graphical user interface (GUI) for drag polar assessment has been developed. Using the developed GUI, a student can interactively captured the flight data when the aircraft is in the trim condition. By using the equilibrium equation of forces, the lift coefficient and the related drag coefficient can be obtained. In order to cover a wider range of lift coefficients data with a limited airspeed variation, the weight of the aircraft are varied while maintaining the CG at a fixed point.

To evaluate the developed GUI and the corresponding data processing capability, a simulated flight testing was performed using X-plane software. The simulated flight testing was conducted by using a Cessna 172 aircraft model, which is already available in the software. The aircraft was trimmed using the autopilot feature, to mimic the actual test on UAV. The obtained data from the flight simulation has been recorded and processed using the developed GUI. The drag polar result from the GUI is then compared to the data directly obtained from the X-Plane output. The comparison shows a significant differences due to several factors that was not taken into account during the simulated test flight, such as the weight change due to fuel burn. Further evaluation, including an actual flight testing, is required to ensure that the developed GUI along with the test procedure can be used by students to generate a drag polar curve for a UAV.

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