Prediction of Aerodynamic Characteristics for Commercial Aircraft based on Open-Source Cruise Flight Data

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Abstrak

Airplane characteristics are interesting to analyze. The characteristics are shown as aerodynamic, structural and propulsion performance which further shows how economical the aircraft is compared to other aircraft. With the development of automatic dependent surveillance - broadcast (ADS-B), open source commercial aircraft flight data can be obtained easily. This study is performed to develop algorithm that can be used to predict aircraft aerodynamic coefficients. The algorithm is a collection of equations developed and simplified in previous studies. It is then used to estimate mass, lift, drag, and thrust forces, lift and drag coefficients, as well as fuel flow of an aircraft throughout the flight based on open source flight data, such as Flightradar24. The resulting lift and drag coefficients from the application of this algorithm are reasonably close within 9 – 14% compared to available references. Flightradar24 data is actually quite accurate for further flight performance analysis.

Keywords: aerodynamic prediction, flight data, flightradar24, flight performance.

Abstract

***Prediksi karakteristik aerodinamika pesawat udara komersial berdasarkan data penerbangan jelajah open-source**: Karakteristik pesawat udara selalu menarik untuk dikaji. Karakteristik sebuah pesawat ditunjukkan sebagai performa aerodinamika, struktural, dan propulsi yang selanjutnya menunjukkan seberapa ekonomis pesawat itu dibandingkan pesawat lain. Dengan berkembangnya automatic dependent surveillance – broadcast (ADS-B), data penerbangan pesawat komersil dapat diperoleh dengan mudah. Penelitian ini dilakukan untuk mengembangkan algoritma yang dapat digunakan untuk memprediksi koefisien aerodinamika pesawat. Algoritma ini disusun dari persamaan-persamaan yang diturunkan dan disederhanakan dalam penelitian-penelitian sebelumnya. Algoritma ini selanjutnya digunakan untuk memperkirakan berat, gaya angkat, gaya hambat, dan gaya dorong, koefisien gaya angkat dan gaya hambat, serta laju aliran bahan bakar pesawat sepanjang penerbangannya dengan memanfaatkan data penerbangan dari sumber terbuka, seperti Flightradar24. Koefisien lift dan drag yang dihasilkan dari penerapan algoritma ini cukup dekat yaitu antara 9 – 14% dibandingkan referensi yang tersedia. Data Flightradar24 sebenarnya cukup akurat untuk analisis performa penerbangan lebih lanjut.*

***Kata kunci**: data penerbangan, Flightradar24, performa pesawat udara, prediksi aerodinamika.*

1. Introduction

Airplane flying characteristics are always interesting to analyze. By knowing the flying performance of aircraft, optimal points can be found, so that aircraft operations can be carried out at these points. In addition, by collecting flight performance data, the capabilities of one aircraft can be compared with each other. Analytically, aircraft performance can be calculated from the aerodynamic characteristics, structure and propulsion system used [1]. Aerodynamic characteristics depend on the aircraft's external configuration, such as control plane deflection, landing gear condition, and the like. Structural characteristics include aircraft weight and wing size. The characteristics of the propulsion system include data on thrust force, fuel consumption, propeller efficiency, and the like.

Aircraft aerodynamic data can be obtained from analytical calculations, using software, or testing both in wind tunnels and flight tests. Structural data is obtained from the design carried out by the aircraft manufacturer. Propulsion data is obtained from the manufacturer of the propulsion system and its integration with the airframe. Aircraft designers collect this data to calculate the aircraft's flying performance and validate it with flight test results. That is why flight data (test results) are very valuable. Airlines operating aircraft also try to obtain and process flight data for their aircraft to ensure whether the aircraft have been operated according to procedures and at its optimal point. Various flight operations

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quality assurance (FOQA) or flight data monitoring (FDM) software are used to process flight data for this purpose [2].

Nowadays, with the development and deployment of ADS-B systems, commercial aircraft flight data can be obtained quite easily. Although these data is quite limited, several methods have been developed to derive information related to aircraft flight performance [3], wind disturbance, and aircraft engine performance [3]. ADS-B data can be freely accessed using internet-based flight tracking platforms such as Flightradar24. Flightradar24 is an application that can display real-time air traffic around the world by combining data from various sources such as ADS-B, MLAT, satellite, and radar [5]. Therefore, Flightradar24 provides promising potential due to its high accessibility. However, no studies have been conducted to determine how accurate the determination of aerodynamic data from open source sources is.

This study aims to develop algorithm that can be used to predict aircraft aerodynamic coefficients. The algorithm is a collection of equations developed and simplified in previous studies. It is then used to analyze aircraft flying performance using data freely available on Flightradar24 [5] to obtain estimates of aircraft aerodynamic coefficients. This application can be accessed through the website using computers and mobile devices. FlightRadar24 displays aircraft ICAO type code, flight number, callsign, registration, origin and destination airports, position, altitude, ground speed and track. Departure times (actual and scheduled) as well as arrival times are also provided along with travelled and remaining distances. Figure 1 shows the main view of flightradar24 website. Real time air traffic is displayed over the world map. The path that has been traversed by the aircraft on the map is also displayed. Each airborne aircraft is marked with an airplane-shaped icon and the flight's callsign. The flight direction of the icon is adjusted according to the real flight direction of each aircraft. Aircraft flight data can also be played back, both for flights in progress and those that have landed. The play back includes aircraft position, flight direction, calibrated altitude, ground speed and ground track.

This method is offered as an alternative to previously developed aerodynamic calculation and estimation methods. With software such as Datcom [6], aircraft aerodynamic characteristics can be predicted easily through the external geometry of the aircraft. However, this method does not provide predictions of aircraft engine characteristics which actually greatly affect the aircraft's flight performance. The same type of aircraft will be predicted to have the same characteristics even though the engines are different. Aircraft characteristics can also be predicted based on flight test data, as explained in [7]. As is well known, flight test method is very costly, time consuming and requires very complex equipment. Unlike flight tests, where almost all data is available and can be obtained through the installation of complete sensors, open source data is very limited. In flight tests, for example, weight and engine setting

Figure 1. Example of flightradar24 display [5].

data are known, while open source data usually does not contain these parameters. So, the algorithm developed is intended to overcome the absence of this data.

2. Methodology

This section describes procedures taken to calculate aircraft aerodynamic coefficients using available open source data. Firstly, initial aircraft weight will be derived from take off analysis. This data is then used to derive thrust values along the trajectory of the aircraft. Engine fuel flow is then calculated based on thrust model obtained. Finally, the aircraft aerodynamic data are calculated.

2.1. Point-Mass Models and Forces Acting on Aircraft

Analysis of flight performance generally uses point-mass model of aircraft. In this approach only the displacement of the point mass of the aircraft is considered, while the attitude of the aircraft is ignored. Forces considered are thrust, lift, drag and weight (Figure 2) and all are acting on the point mass. Aerodynamic forces are usually derived from lift and drag coefficients, C_L and C_D, which will be calculated in this study. Aircraft initial weight at the start of take off is considered as the first most important parameter to be determined in performance analysis. Since this data is usually unavailable from any open-sources, assumptions have to be used. The most important one is that pilots always perform take off maneuvers according to aircraft manuals. Then, initial weight of aircraft can be predicted based on take off distance.

Take off is defined as a maneuver in which an aircraft accelerates from rest on the runway until it reaches a screen height of 10.7 m (35 ft) for civilian transport aircraft [1]. The heavier the aircraft, the longer the takeoff distance and time required. This distance can be calculated using aircraft climb profile (altitude vs time) or (altitude vs distance). Alternatively, take off distance can also be calculated indirectly from rate of climb time history. Then, using takeoff weight limitation chart on aircraft manuals such as [8], initial weight of the aircraft can be estimated based on the obtained takeoff distance.

From there, thrust can be calculated from the known weight of the aircraft using the following relationships (1) and (2) [1],

$$L = W \cos\gamma \tag{1}$$

$$T = D + W \sin\gamma \tag{2}$$

where L is lift, W is aircraft weight, γ is flight path angle, T is thrust and D is drag.

Drag can be calculated from lift using polar drag, where the lift coefficient C_L is (3),

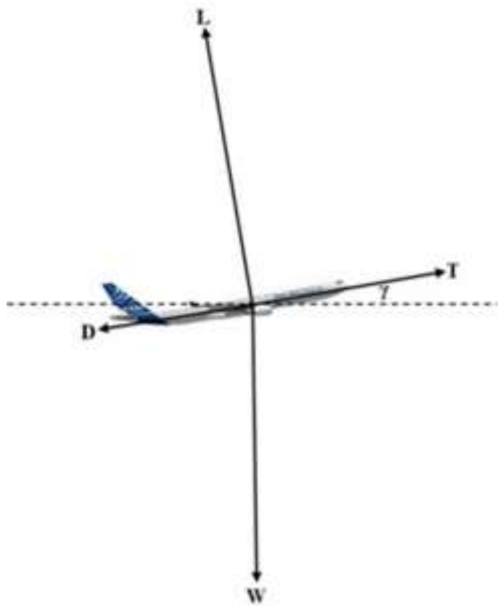

Figure 2. Forces acting on an aircraft using point-mass model.

$$C_L = \frac{L}{\frac{1}{2}\rho V_{TAS}^2 S} \tag{3}$$

and drag coefficient C_D is (4),

$$C_D = C_{D_0} + k\, C_L^2 \tag{4}$$

with drag D formulated as (5),

$$D = \frac{1}{2}\rho V_{TAS}^2\, S\, C_D \tag{5}$$

In the above equations ρ is the air density, V_{TAS} is the true airspeed, S is the aircraft wing reference area, C_{D0} is zero-lift drag coefficient and k is lift-induced drag coefficient.

2.2. Thrust Models for Turbofan Engines

Next important variable to be determined is the aircraft thrust. Thrust model is used to calculate maximum thrust that can be provided by a turbofan engine as function of altitude, speed and throttle setting. There are two thrust models, one model for takeoff analysis and another for en-route flight at various altitudes as explained below.

2.2.1. Thrust for Take off Phase

Maximum take-off thrust is calculated as the ratio of the maximum static thrust and can be modeled as a second-order polynomial function of velocity [8]. The coefficients of this equation depend on the engine bypass ratio λ and pressure ratio δ as given in [9] as follows (6),

$$\frac{T_{max}}{T_0} = A - \frac{0.377(1+\lambda)}{\sqrt{(1+0.82\lambda)\,G_0}}\, Z\, M + \left(0.23 + 0.19\sqrt{\lambda}\right) X\, M^2 \tag{6}$$

where T_{max} is maximum thrust, T_0 is maximum static thrust, M is Mach number and G_0 is the function coefficient of the bypass ratio (7),

$$G_0 = 0.0606\lambda + 0.6337 \tag{7}$$

A, Z and X are coefficients related to pressure ratios to account for runway elevation as follows (8),

$$\delta = \frac{p}{p_0} \tag{8}$$

where p is the local air pressure and p_o is sea-level pressure. Then using (9), (10), and (11),

$$A = -0.4327\delta^2 + 1.3855\delta + 0.0472 \tag{9}$$

$$Z = 0.9106\delta^3 - 1.7736\delta^2 + 1.8697\delta \tag{10}$$

$$X = 0.1377\delta^3 - 0.4374\delta^2 + 1.3003\delta \tag{11}$$

2.2.2. Thrust for En-Route Phases

For en-route phase, maximum thrust is modeled to the net thrust at the reference cruising condition T_{cr}. Alternatively, cruise thrust can be calculated using the following empirical equation (12) [10],

$$T_{cr} = 0.2T_0 + 890 \tag{12}$$

This thrust calculation also depends on the reference cruise Mach number M_{cr} and calibrated airspeed $V_{CAS,\,cr}$ on cruising altitude h_{cr}. The calculations are divided into three segments based on aircraft altitude as derived in [9].

a) Flight Segments above 30,000 ft

For calculating maximum thrust at an altitude of 30,000 ft up to the service ceiling of aircraft, the following equation (13),

$$\frac{T_{max}}{T_{cr}} = c_1 \ln\left(\frac{p}{p_{cr}}\right) + c_2 \tag{13}$$

where p is air pressure, while c_1 and c_2 are calculated using the following equations (14) and (15),

$$c_1 = -0.4204\left(\frac{M}{M_{cr}}\right) + 1.0824 \quad (14)$$

$$c_2 = \left(\frac{M}{M_{cr}}\right)^{-0.11} \quad (15)$$

b) Flight Segments from 10,000 to 30,000 ft

The following is the equation used to calculate maximum thrust at altitudes between 10,000 ft to 30,000 ft is calculated using the following equation (16)

$$\frac{T_{max}}{T_{cr}} = c_3\left(\frac{p}{p_{cr}}\right)^{c_4} \quad (16)$$

where c_3 and c_4 are calculated as follows (17)

$$c_3 = \left(\frac{V_{CAS}}{V_{CAS,cr}}\right)^{-0.1} \quad (17)$$

$$c_4 = -0.335\left(\frac{V_{CAS}}{V_{CAS,cr}}\right) + c_5 \quad (18)$$

The value of c_5 is based on lookup table, but a linear approach to c_5 from [12] can also be used to make computation easier, where (19)

$$c_5 = 2.667\ x\ 10^{-5}\ VS + 0.8633 \quad (19)$$

c) Flight Segments up to 10,000 ft

For the initial climbing phase up to a height of 10,000 ft, a linear model is used to estimate the thrust ratio as follows (20),

$$\frac{T_{max}}{T_{cr}} = c_6\left(\frac{p}{p_{cr}}\right) + \left[\frac{T_{10}}{T_{cr}} - c_6\left(\frac{p_{10}}{p_{cr}}\right)\right] \quad (20)$$

where T_{10} is the maximum thrust at 10,000 ft calculated using (16) to (19), while c_6 is a coefficient to account for speed variations. Reference [10] uses approximate equation to find c_6 as follows (21),

$$c_6 = -0.12043\left(\frac{V_{CAS}}{V_{CAS,cr}}\right) - 8.8889x10^{-9}\ VS^2 + 2.4444x10^{-5}\ VS + 0.47379 \quad (21)$$

Total aircraft thrust can then be calculated as (22),

$$T_i = T_{max,i}\frac{N1}{100} \quad (22)$$

where $N1$ depends on aircraft altitude and airspeed, obtained from [13].

2.3. Fuel Flow Models

Fuel flow model can be formulated based on the ICAO Aircraft Engine Emission Data-Bank [14]. This data can be used to model aircraft fuel flow in idle (7% power), approach (35%), climb-out (85%) and takeoff (100%) powers. Third order polynomial fitting is carried out to obtain the following equation (23) [12],

$$f_{fuel}(T,h) = C_{ff3}\left(\frac{T}{T_0}\right)^3 + C_{ff2}\left(\frac{T}{T_0}\right)^2 + C_{ff1}\left(\frac{T}{T_0}\right) + C_{ff,ch}\ T\ h \quad (23)$$

where C_{ffi} are correction factors that depend on engine type and $C_{ff,ch}$ is linear correction factor calculated using cruise specific fuel consumption SFC_{cr} to account for altitude effects as follows (24),

$$C_{ff,ch} = \frac{SFC_{cr} - \frac{f_{fuel,SL}(T_0)}{T_0}}{h_{cr}} \quad (24)$$

The mass of the aircraft at the next point in time is calculated using the assumption that fuel is constant from the current point in time to the next point in time, or (25),

$$m_{i+1} = m_i - f_{fuel}(t_{i+1} - t_i) \quad (25)$$

2.4. Aircraft Drag Polar

For a point-mass aircraft the relationship between C_L and C_D can be simplified into a polar drag represented by (4). C_{D0} and k depend on aircraft configuration, such as flaps deflection and landing gear extension. In addition, when an airplane flies at a high Mach number (transonic), there are wave drag caused by local supersonic flows and shock waves (which will be ignored here). Thus, polar drag with these effects can be represented by the following equations (26), (27), and (28),

$$C_{D0,total} = C_{D0} + \Delta C_{D,f} + \Delta C_{D,g} + \Delta C_{D,w} \quad (26)$$

$$k_{total} = \frac{1}{1/k + \pi A \Delta e_f} \quad (27)$$

$$C_{D,total} = C_{D0,total} + k_{total} C_L^2 \quad (28)$$

where $\Delta C_{D,f}$ is drag due to flaps deflection, $\Delta C_{D,g}$ is drag due to landing gear extension, and $\Delta C_{D,w}$ is wave drag. Here, A is the wing aspect ratio and Δe_f is the change in the Oswald factor due to additional drag.

For airborne time points, several other parameters needed for function input (but not available in the CSV downloaded from [5]) are calculated first using the following equation based on ground speed and altitude time history (29), (30), and (31)

$$ROC_i = \frac{h_{i+1} - h_i}{t_{i+1} - t_i} \quad (29)$$

$$V_i = \sqrt{V_{h,i}^2 + ROC_i^2} \quad (30)$$

$$\gamma_i = tan^{-1}\left[\frac{h_{i+1} - h_i}{\frac{1}{2}(V_{h,i+1} + V_{h,i})(t_{i+1} - t_i)}\right] \quad (31)$$

where ROC is aircraft rate of climb, V is true airspeed, V_h is horizontal velocity and γ is flight path angle.

Overall, the sequence of using the equations explained above is shown in Figure 3.

3. Result and Analysis

The above method is then applied to Airbus aircraft A330-343 data, flight no. GA960 flying from CGK to MED on June 10, 2023 based on record downloaded from [5]. The data is assumed to be 100% correct, by neglecting any inaccuracies in the sensors and recording, then used as it is, without any pre-processing.

3.1. Climb Profile Analysis

According to the above flowchart, the weight of the aircraft at the start of the flight needs to be determined first. Initially, the climb performance table from [13] is compared with the real flight climb profile to obtain an initial estimate of the aircraft's weight. The result is shown in Figure 4.

From Figure 4, it can be stated that the climb profile in real flight does not follow the climb performance table from flight manual which uses maximum thrust. Therefore, the initial weight estimation method based on the climb performance table was considered unsuccessful. This mismatch between the climb profile and the climb performance table can be caused by factors such as the use of non-maximum climb thrust to save fuel, different speed and acceleration profiles other than those given in manual, and different climb procedures to comply with clearance from ATC.

3.2. Aircraft Initial Weight Prediction

Based on observations of the climb profile of the flight, a pattern was obtained that the flight was flying uphill close to the climb performance for an aircraft with a certain weight, but at the beginning and end of the flight it could climb faster than it should, even reaching a final altitude that was more than the maximum altitude. that can be achieved by an aircraft of that weight.

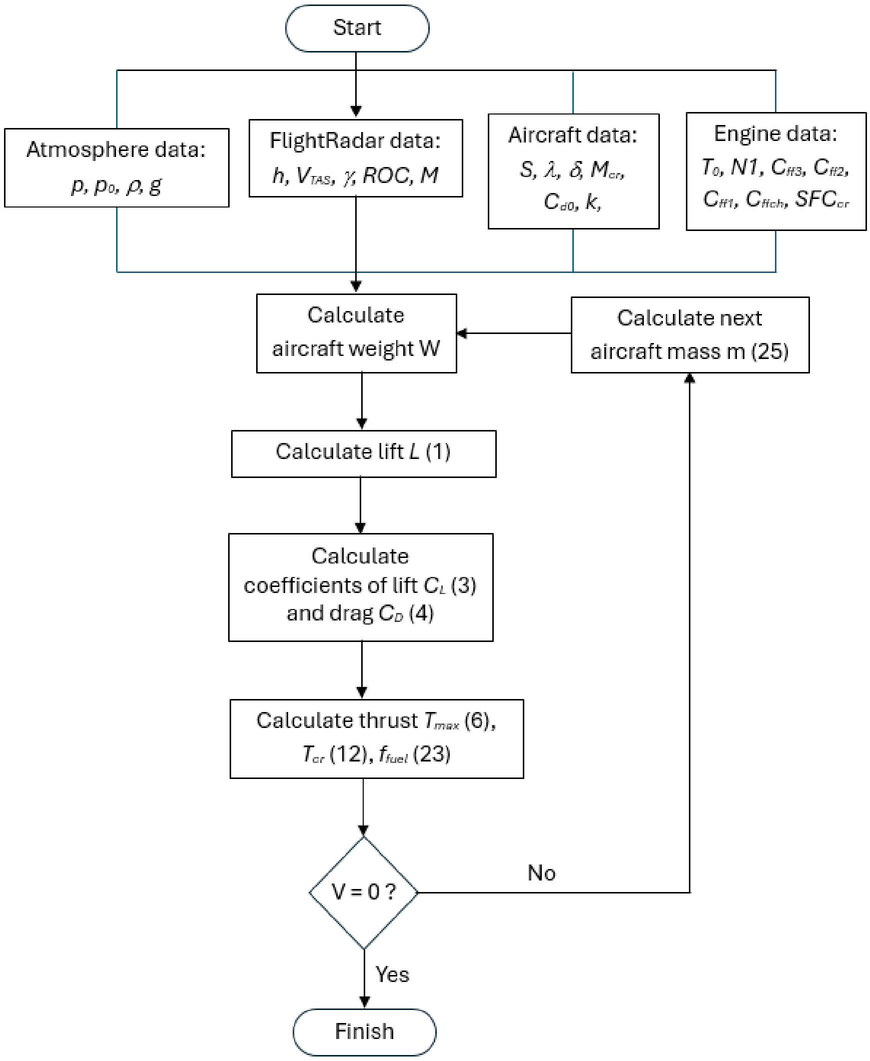

Figure 3. Flowchart of calculations with equation number used.

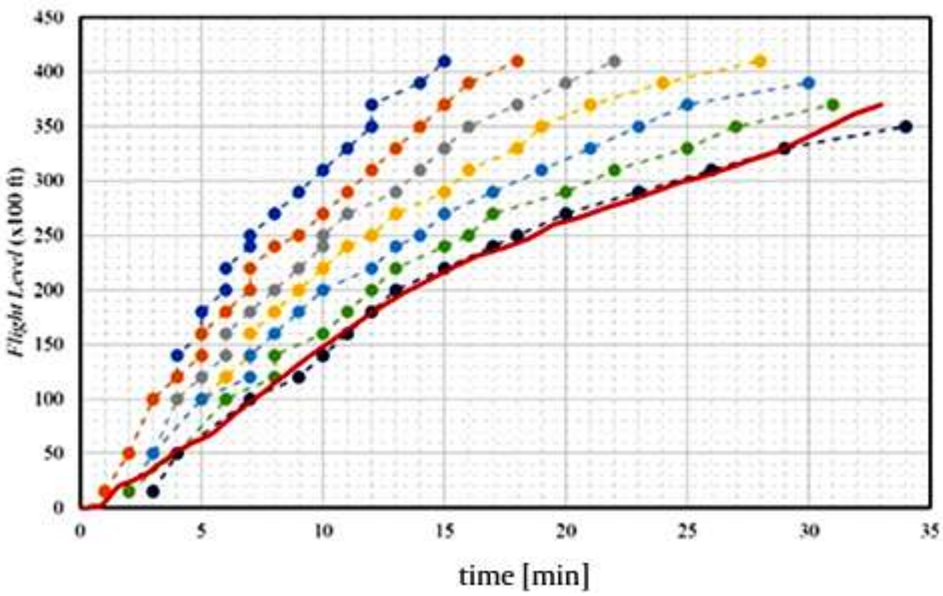

Figure 4. Climb performance comparison of flight manual and actual data [5][13].

The initial weight prediction of the aircraft was then carried out based on takeoff distance analysis. Three types of data is available, namely calibrated altitude, GPS altitude and rate-of-climb time histories. As shown in Figure 5 both calibrated and GPS altitudes were not suitable for further calculation due to its fluctuating and uncertain in nature.

Rate of climb data is then used as a reference for determining takeoff time. For example, on this flight, at the 47th second the climb rate was still zero and at the 56th second the plane already had a positive rate of climb of 320 fpm, so the plane's takeoff time was just slightly after 56 s.

Takeoff distance analysis was carried out using integration method. Rate of climb integration is used to find the point in time at which the aircraft reaches 35 ft altitude, while ground speed integration is used to calculate the takeoff distance. This calculation results in take off time 57 s and take off distance between 2,639 – 2,647 m. Comparing the distance with similar data from [8] gives prediction of initial aircraft weight between 235,184 – 235,380 kg.

3.3. Estimation of Lift and Drag Coefficients

Figure 6 displays the results of estimating the aircraft's weight throughout the flight. GA960 took off from Jakarta weighing 235,380 kg and arrived in Medina weighing 167,915 kg. The aircraft weight variation here is considered reasonable because it is still within the limits between operating empty weight (OEW) of 122,000 kg with 42,000 kg payload (PL) and maximum takeoff weight (MTOW) of 242,000 kg.

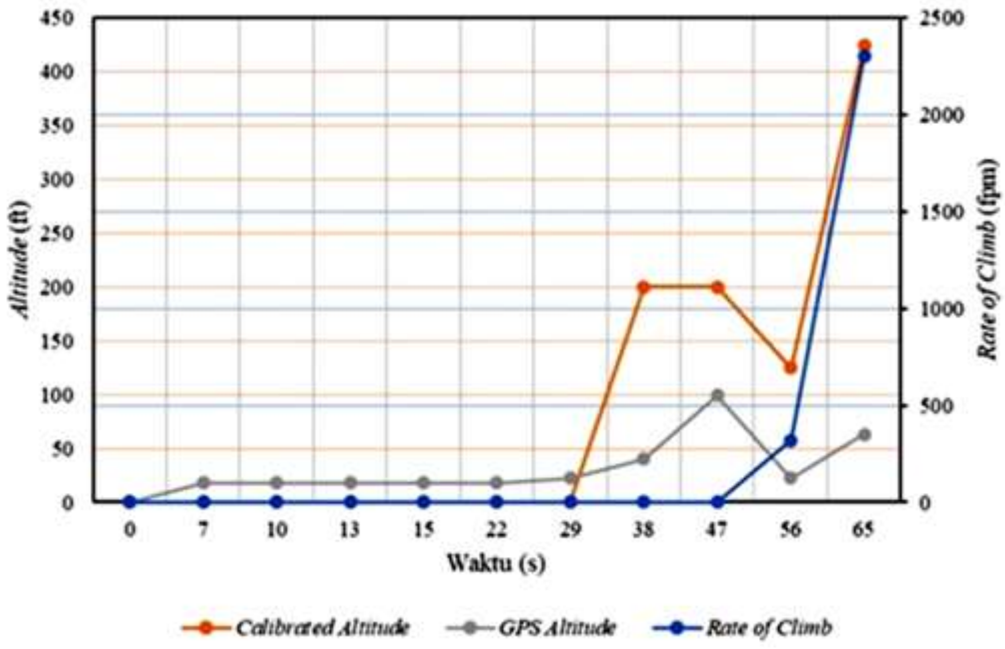

Figure 5. Altitude and rate-of-climb time histories [5].

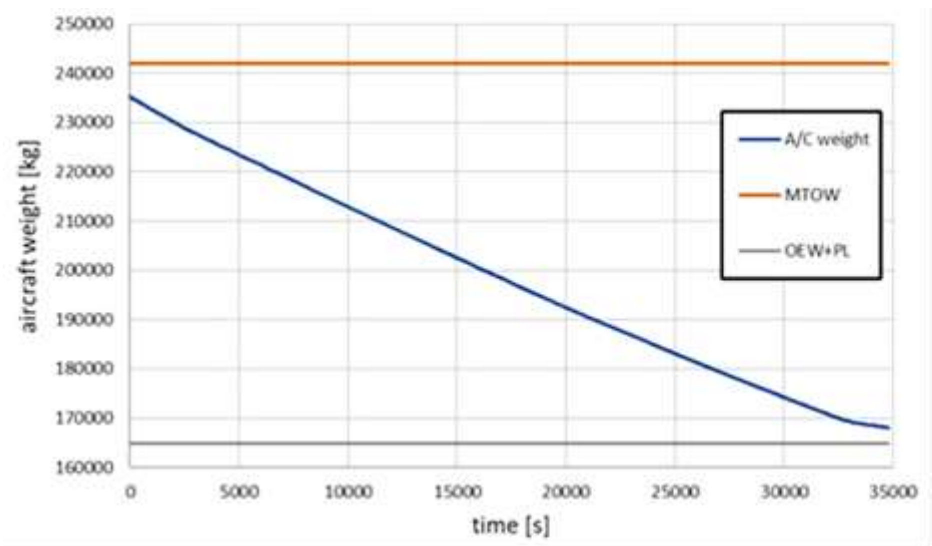

Figure 6. GA960 weight time history.

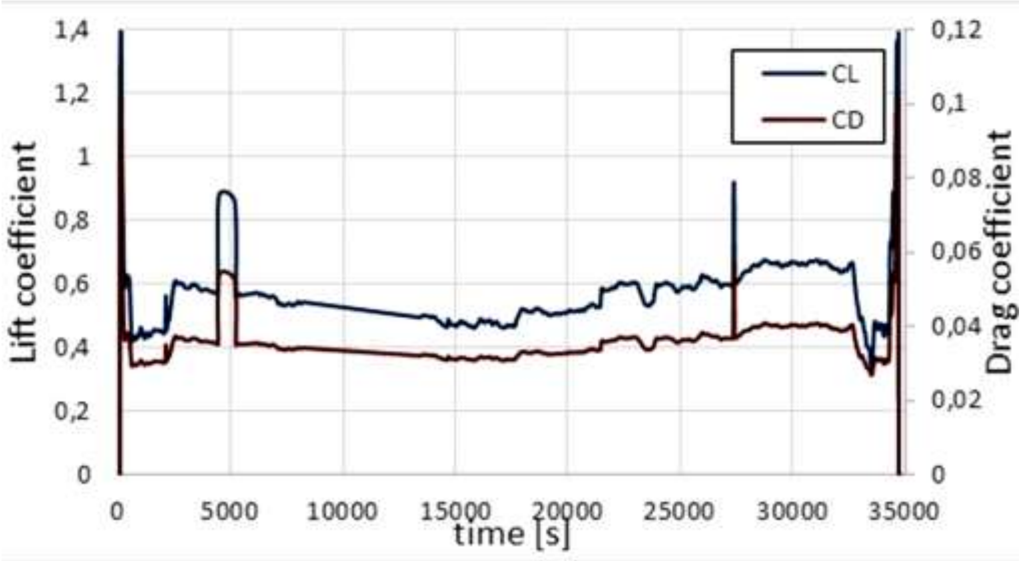

Figure 7. Calculated lift and drag coefficients for selected flight [5].

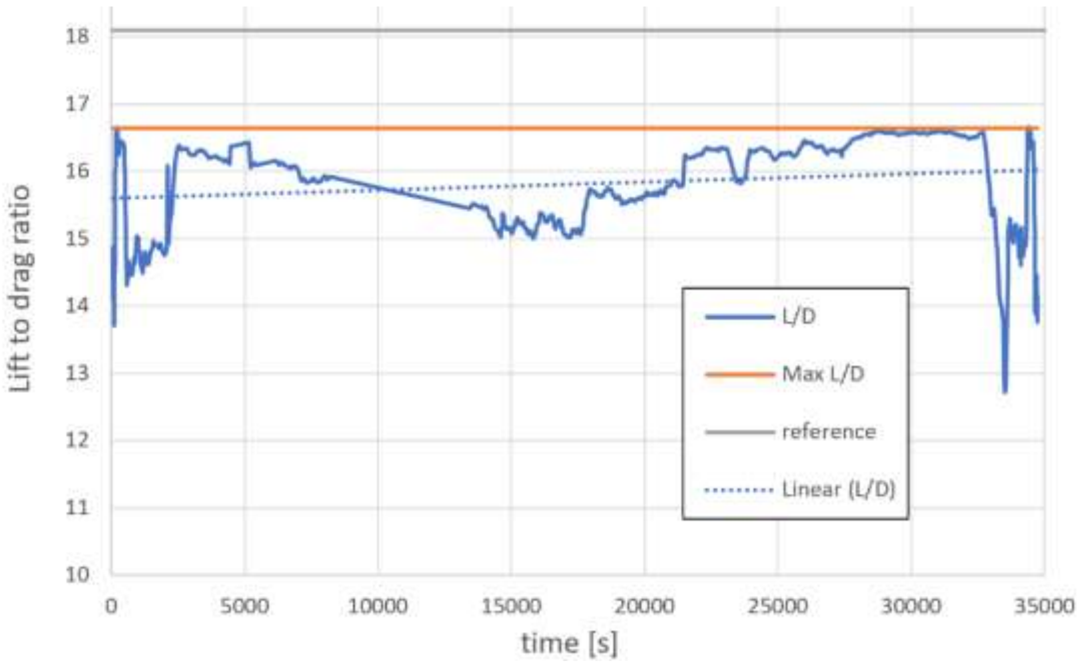

Figure 8. Calculated lift and drag coefficients for selected flight [5].

By following the calculation sequence as shown in Figure 3, the lift and drag coefficients of the aircraft can then be calculated. As seen in Figure 3, in addition to data from FlightRadar, atmospheric condition, aircraft and engine data are also required. References [8][10][14] can be used to find the necessary additional data. Figure 7 displays the resulted lift and drag coefficients throughout the flight. It can be seen that the obtained C_L and C_D values are within reasonable values. However, some points exist in red circles showing inaccuracies of measurements and/or data recording, since data is used directly from downloaded results without any pre-processing.

Lift to drag (L/D) is shown in Figure 8. The linear trendline shows that L/D varies from approximately 15.6 to 16.0. This value is considered reasonable when compared with the maximum L/D of the polar drag used, which is 16.6 at C_L 0.732. This value is quite low when compared to data of the same aircraft type from [15] which gives the average value of 18.1 for cruise condition, so the differences are between 9 – 14%.

4. Conclusion

The conclusions drawn from this study are, An algorithm has been developed to predict aircraft aerodynamic coefficients. The algorithm is composed of equations developed in previous studies and simplified. It is then applied to analyze aircraft flight data downloaded from Flightradar24. Open-sourced data, such as that obtained from [5], can be used to calculate aircraft's aerodynamic coefficients using the proposed method. In contrast to the Datcom and flight test methods explained previously, with this method characteristics of the aircraft can be predicted by also considering the propulsion system used. The predicted results are reasonable within 9 – 14% tolerance. Future works include development of method to derive aerodynamic coefficients from open-source flight data without relying on aircraft manuals or other references. Many number of flight records can be used to remove this dependency. In addition, when the exact time of flap deflection and landing gear extraction are known, it is also possible to separate the effects of flaps and landing gear in calculating lift and drag coefficients.

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