Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Estimation of Drag Polar for ABT-18 Unmanned Aerial Vehicle

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ARTICLE INFORMATION

Article history:
Received 02 Mar, 2021
Revised 14 Jun, 2021
Accepted 15 Jun, 2021
Available online 30 Jun, 2011

Keywords:
Aerodynamics
Aircraft performance
Induced drag
Optimization
Parasite drag

ABSTRACT

An aircraft travelling through air generates aerodynamic forces known as drag and lift forces which will affect its general performance. Several approaches including computational fluid dynamics (CFD), experimental (wind tunnel) and analytical methods have been used to explain, estimate and optimize drag forces during aircraft design. This work compares the drag polar forces of a standard ABT-18 to a modified ABT-18, which is modified to an unmanned aerial vehicle (UAV). As part of an extension of service life programme of the Nigerian Air Force, the ABT-18 is being converted into a UAV. As such, this study attempts to derive an accurate and simple mathematical model to estimate the drag polar of the UAV version of the ABT-18. The results of the estimation for the parabolic drag polar of the ABT-18 UAV has been obtained successfully. This was achieved using an analytical method. However, the CFD method could be employed to further investigate the aerodynamic characteristics of the ABT-18 UAV for proper performance optimization.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have found applications in fields like agriculture, medical logistics in addition to military applications (Triet et al., 2015; Karthik et al., 2017; Yayli et al., 2017; Khuntia and Ahuja, 2018). As an aircraft travels through air, aerodynamic forces – drag and lift forces – are generated (Lubyana and Adhitya, 2020). The drag forces impede the forward motion of the aircraft while the lift acts perpendicular to the aircraft thereby causing the aircraft to become airborne. This lift force is generated by the aircraft as a result of differential pressure between its bottom and top surfaces (Narendiranath et al., 2017; Lubyana and Adhitya, 2020). The drag force is divided into two; zero-lift and induced drag. The former also known as parasite drag is propositional to the square of the airspeed. This denotes the aerodynamic neatness relating to characteristics of friction, shape and protrusions. As the aircraft speed increases, the magnitude of zero-lift drag increases and is the key element in defining the maximum speed of the aircraft.

Drag estimation is essential for aircraft performance, to ensure that the best possible approximation of all the various types of drag related to aircraft aerodynamics (Kundu et al., 2016). Optimization of drag increases maximum efficiency, thus, increasing the overall performance of the aircraft (Sun et al., 2018; Thu et al., 2018). An aircraft aerodynamics characteristic may be mathematically demonstrated and obtained by a variety of methods such as computational fluid dynamics (CFD), experimental using a wind tunnel and analytical methods (Akgun et al., 2016; Mohammad, 2017). Nevertheless, the CFD method is used to complement both the experimental and analytical studies to improve the design as it reduces the expense for tests and time (Bitencourt et al., 2011; Shreyas et al., 2014; Akgun et al., 2016; Manikantissar and Ankur, 2017; Sharma et al., 2019). This work compares the drag polar forces of a standard ABT-18 to a modified ABT-18, which is modified to an unmanned aerial vehicle (UAV). It attempts to derive an accurate and simple mathematical model to estimate the drag polar of the ABT-18 UAV.

2. METHODOLOGY

2.1. Drag Polar Estimation of ABT-18 UAV

The drag and the drag coefficient can be presented in several forms. Nevertheless, for directness and clarity, the parabolic representation has been opted for in this study. The universal equation for the parabolic drag polar is shown in Equation (1) (Thu et al., 2018; Sancha, 2019).

$$C_D = C_{D0} + KC_L^2 \tag{1}$$

Where C_{D0} is the parasite drag coefficient, K represents induced drag correction factor, and the lift coefficient is represented by C_L. The product of K and C_l represents the lift induced drag and its impact at low speed is maximum (Mohammad, 2017). Equation 1 suggests that the aerodynamic force of drag depends on the parasite drag coefficient (C_{D0}).

2.2. Parasite Drag (C_{D0}) for ABT-18 at Cruise

The parasite drag coefficient or zero-lift drag coefficient (C_{D0}) is obtained using the build-up technique where C_{D0} is defined as follows (Mohammad, 2017).

$$C_{D0} = C_{D0f} + C_{D0w} + C_{D0ht} + C_{D0vt} + C_{D0LG} + C_{D0S} + C_{D0HLD} + \cdots \tag{2}$$

$C_{D0f}, C_{D0w}, C_{D0ht}, C_{D0vt}, C_{D0HLD}, C_{D0LG},$ and C_{D0s} signify the fuselage, wing, horizontal tail, vertical tail, high lift devices, landing gear and landing gear strut impact on the aircraft respectively. The C_{D0} added by high lift aids may be ignored at cruise for the ABT-18 UAV. Table 1 presents some of the performance, aerodynamic and structural dimensions of ABT-18 UAV.

Zero-lift drag generated by the fuselage:

The coefficient of parasite/zero-lift drag generated by the fuselage is shown in Equation 3.

$$C_{D0f} = C_f f_{LD} f_M \frac{S_{wetf}}{S} \tag{3}$$

The function for fuselage length-to-diameter ratio, (f_{LD}) is represented as:

$$f_{LD} = 1 + 60\left(\frac{L}{D}\right)^{-3} + 2.5 \times 10^{-3}\left(\frac{L}{D}\right) \tag{4}$$

C_f is a dimensionless coefficient of skin friction and is calculated based on the relationship of Prandtl as follows:

For turbulent flow:

$$C_f = \frac{0.455}{[log_{10}Re]^{2.58}} \quad (5)$$

For laminar flow:

$$C_f = \frac{1.327}{\sqrt{Re}} \quad (6)$$

$$Re = \frac{\rho VL}{\mu} \quad (7)$$

Re is the Reynolds number.

Table 1: Performance and aerodynamic requirements of ABT-18 UAV (Ananwune, 2015)

Constraint	Dimension
Cruise altitude	5,000 m
Cruise speed	150 kts
Coefficient of viscosity (μ)	0.0000147
Density at cruise altitude (ρ)	0.9629
Wing reference area (S)	10.2 m^2
Mean aerodynamic chord ($\bar{c}$)	1.46 m
Wing aspect ratio	4.8
Oswald efficiency	0.65

Wings zero-lift drag:

Since the wing, vertical and horizontal tails are the surfaces for lifting the aircraft; therefore, they are evaluated similarly. The zero-lift drag coefficients of these lifting surfaces are given by Equations 8 – 10.

$$C_{D0w} = C_{fw} f_{tcw} f_M \left(\frac{S_{wet_w}}{S}\right)\left(\frac{C_{Dmin_w}}{0.004}\right)^{0.4} \quad (8)$$

$$C_{D0ht} = C_{fht} f_{tcht} f_M \left(\frac{S_{wet_{ht}}}{S}\right)\left(\frac{C_{Dmin_{ht}}}{0.004}\right)^{0.4} \quad (9)$$

$$C_{D0vt} = C_{fvt} f_{tcvt} f_M \left(\frac{S_{wet_{vt}}}{S}\right)\left(\frac{C_{Dmin_{vt}}}{0.004}\right)^{0.4} \quad (10)$$

What has been defined for fuselage in Equation (3) is similar to $C_{fw}, C_{fht}, and\ C_{fvt}$ in these equations for the wing, horizontal and vertical tails respectively. However, the equivalent value of L in Equation 7 for the wing, horizontal and vertical tails is different which is their mean aerodynamic chord (MAC).

Landing gears zero-lift drag:

The landing gear of the ABT-18 UAV is an immovable type. According to Mohammad, (2017), the component of zero-lift drag of immovable landing gears may be estimated via Equations 11 and 12.

$$C_{D0_{lg}} = \sum_{i=1}^{n} C_{Dlg} \left\{\frac{S_{lgi}}{S}\right\} \quad (11)$$

$$S_{lg} = d_g w_g \quad (12)$$

$$C_{D0_{lg}} = \frac{C_{D_{lg}}}{S} \sum_{i=1}^{n} S_{lgi}$$

Where S_{lg} is the frontal area of each wheel, S is the wing reference area. C_{Dlg} is the drag coefficient of the wheel and when the wheel of the landing gear has fairing according to Mohammad, (2017), $C_{D_{lg}} = 0.15$ and 0.30 when it does not have any fairing. An *aircraft fairing* is a structure whose primary function is to produce a smooth outline and reduce drag, such as an airfoil (Mohammad, 2017). The d_g and w_g represent the diameter and width of the wheel.

The landing gears strut zero-lift drag:

The increase in C_{D0} according to Mohammad, (2017) due to the application of strut is shown in Equation 13.

$$C_{D0_s} = \sum_{i=1}^{n} C_{D0si} \left\{\frac{S_s}{S}\right\} \tag{13}$$

Where C_{D0_s}, S_s, and S represent the drag coefficient, frontal area of each of the strut and wing reference area. The C_{D0_s} for an airfoil section is 0.1.

Installed camera zero-lift drag:

The estimation procedure of zero-lift drag for the camera is similar to that of strut and landing gears. The method for calculating the zero-lift drag due to the surveillance camera is in Equation 14:

$$C_{Dcam} = \sum_{i=1}^{n} C_{D0cam} \times \left\{\frac{S_{cami}}{S}\right\} \tag{14}$$

The C_{D0cam} and S_{cami} are the camera minimum drag and camera wetted area respectively.

Camera minimum drag:

$$C_{D0cam} = 0.5\ (for\ solid\ sphere)$$

The camera wetted area is obtained from Ananwune, (2015):

$$S_{cami} = 0.101\ m^2$$

2.3. Lift Induced Drag Estimation for the ABT-18 UAV

The lift induced drag is the drag due to the generation of lift. Thus, as the angle of attack of an aircraft changes, this form of drag changes. From Equation (1), the induced drag is thus presented in Equation 15 which is defined as a function of lift coefficient.

$$C_{Di} = KC_L^2 \tag{15}$$

$$K = \frac{1}{\pi \times AR \times e} \tag{16}$$

Where the aspect ratio of a wing is *AR*, and *e* is the Oswald efficiency factor.

3. RESULTS AND DISCUSSION

3.1. Zero Lift Drag Estimation

3.1.1. Zero-lift drag generated by the fuselage

The cruising speed of ABT-18 UAV is 150 knots (79.7 m/s) at an altitude of 5,000 m. Therefore:

$$R_e = \frac{(6.15 \times 0.96287 \times 79.7)}{14.7 \times 10^{-6}} = 32105819$$

Since, $R_e > 2 \times 10^6$, then the flow around the fuselage is considered turbulent. Thus:

$$C_f = \frac{0.455}{[log_{10}32105819]^{2.58}} = 0.0025$$

The function for fuselage length-to-diameter ratio, (f_{LD}) from Equation 4:

$$f_{LD} = 1 + \frac{60}{(5.8)^3} + 0.0025(5.8) = 1.322$$

The Mach number function, (f_M) from Equation (3) is defined as:

$$f_M = 1 - (0.08 \times M^{1.45}) \approx 1 \qquad \text{(low subsonic aircraft)}$$

As obtained from Ananwune, (2015), the wetted area of the fuselage, $S_{wetf} \approx 26\ m^2$

From Table 1, the wing reference area = $10.2\ m^2$

Hence from Equation 3:

$$C_{D0f} = 2.5 \times 10^{-3} \times 1.322\left(\frac{26}{10.2}\right) = 0.00842$$

3.1.2. Wings zero-lift drag

For the ABT-18 UAV wing at a cruise, Equation (7) gives:

$$Re = \frac{0.96287 \times 79.7 \times 1.46}{1.47 \times 10^{-5}} = 7621869$$

and

$$C_{fw} = \frac{45.5 \times 10^{-2}}{[log_{10} 7621869]^{2.58}} = 31.4 \times 10^{-4}$$

The second term of Equations (8), (9) and (10), (f_{tc}) is defined as:

$$f_{tc_w} = 1 + 2.7\left({}^{t}/_{c}\right)_{max} + 100\left({}^{t}/_{c}\right)^4_{max} \tag{17}$$

The ${}^{t}/_{c}$ of the wing of ABT-18 UAV is given as 13.5% as obtained in Ananwune, (2015). Hence, $f_{tc} = 1.4$.

The wetted area of the wing:

$$S_{wet_w} = 2\left[1 + \frac{1}{2}\left({}^{t}/_{c}\right)_{max}\right]bc \tag{18}$$

$$S_{wet_w} = 21.82\ m^2$$

The parameter C_{Dmin} in Equations (8), (9) and (10) gives the minimum coefficient of drag of the airfoil cross-section for the wing or tail. The airfoil section of the ABT-18 UAV wing is NACA23013.5 and its corresponding C_{Dmin} is 0.006. Therefore:

$$C_{D0w} = 0.00314 \times 1.4 \times 1 \times \left(\frac{20.92}{10.2}\right)\left(\frac{0.006}{0.004}\right)^{0.4}$$

$$C_{D0w} = 0.011$$

3.1.3. Horizontal tail zero-lift drag

The zero-lift drag of the horizontal tail of the ABT-18 UAV can be estimated from Equation (9).

$$Re = \frac{0.96287 \times 79.7 \times 0.796}{0.0000147} = 4155485$$

$$C_{fht} = \frac{0.455}{[log_{10}4155485]^{2.58}} = 0.00347$$

$$f_{tc} = 1 + 2.7(0.12) + 100(0.12)^4 = 1.345$$

Wetted area for the tail-plane as obtained in Ananwune, (2015):

$$S_{wet_{ht}} = 4.506\, m^2$$

$$C_{Dmin} = 0.005$$

$$C_{D0ht} = 0.00347 \times 1.345 \times 1 \times \left(\frac{4.506}{10.2}\right)\left(\frac{0.005}{0.004}\right)^{0.4} = 0.00225$$

3.1.4. Vertical tail zero-lift drag

The zero-lift drag of the vertical tail of the ABT-18 UAV can be estimated as well from Equation (10).

$$Re = \frac{0.96287 \times 79.7 \times 1.438}{0.0000147} = 7507019$$

$$C_{fht} = \frac{0.455}{[log_{10}7507019]^{2.58}} = 0.00315$$

$$f_{tc_{vt}} = 1 + 2.7(0.12) + 100(0.12)^4 = 1.345$$

$$S_{wet_{vt}} = 2\left[1 + 0.5\left(\frac{t}{c}\right)_{max}\right] bc = 3.6\, m^2$$

$$C_{D0vt} = 0.00315 \times 1.345 \times 1 \times \left(\frac{3.6}{10.2}\right)\left(\frac{0.005}{0.004}\right)^{0.4} = 0.0016$$

3.1.5. Landing gears zero-lift drag

With fairings on each wheel of the ABT-18 UAV:

$$C_{D0_{lg}} = \frac{0.15}{10.2} \times \{(0.32 \times 0.12) + 2(0.42 \times 0.15)\} = 0.0024$$

3.1.6. The landing gears strut zero-lift drag

For ABT-18, the strut area of the nose gear:

$$S_s = 0.03 \times 0.56 = 0.0168\, m^2$$

Strut area of the main gear:

$$S_s = 0.15 \times 0.67 = 0.01005\, m^2$$

The minimum drag of nose gear strut:

$$C_{D0si} = 0.1(airfoil\ section)$$

The minimum drag of main gear strut:

$$C_{D0si} = 1.2\ (convex\ faced\ semicircular\ rod)$$

$$C_{D0s} = \frac{(0.0168 \times 0.1) + (0.01005 \times 1.2)}{10.2} = 0.00135$$

3.1.7. Installed camera zero-lift drag

From Table 1, the ABT-18 wing reference area = 10.2 m^2.

Thus:

$$C_{Dcam} = 0.5 \times \frac{0.101}{10.2} = 0.0050$$

Hence, to compute the overall zero-lift drag of ABT-18 UAV the correction factor, Kc from Equation (2) is subject to numerous factors; the type, degree of fuselage streamlines, year of fabrication, aircraft configuration and the number of miscellaneous items. Table 2 presents different correction factors for various aircraft configurations.

Table 2: Table showing the values of K_C for various aircraft configuration (Mohammad, 2017)

Aircraft	K_C
Jet transport	1.1
Agriculture	1.5
Prop driven cargo	1.2
Single engine piston	1.3
General aviation (GA)	1.2
Fighter	1.1
Glider	1.05
Remote controlled	1.2

From Table 2, the aircraft belongs to the general aviation aircraft group. Hence, K_c *is* 1.2 for ABT-18 UAV. Therefore, from Equation 2 the overall zero-lift drag on the aircraft is obtained to be:

$$C_{D0} = 1.2 \times (0.00842 + 0.011 + 0.00225 + 0.0016 + 0.0024 + 0.00135 + 0.0050) = 0.0384$$

3.2. Lift Induced Drag Estimation

For estimation of the lift induced drag for an aircraft, finding the Oswald efficiency, *e* is important. Table 3 present the list of ideal values for C_{D0} and Oswald efficiency, *e* for some configurations of aircraft.

Table 3: List of ideals for C_{D0} and e for several configurations of aircraft (Mohammad, 2017)

Aircraft type	C_{D0}	*e*
Twin engine piston prop	0.022-0.028	0.75-0.8
Large turbo prop	0.018-0.024	0.8-0.85
Small GA with retractable landing gear	0.02-0.03	0.75-0.8
Small GA with fixed landing gear	0.025-0.04	0.65-0.8
Agricultural aircraft with crop duster	0.07-0.08	0.65-0.7
Agricultural aircraft without crop duster	0.06-0.065	0.65-0.75
Subsonic jet	0.014-0.02	0.75-0.85
Supersonic jet	0.02-0.04	0.6-0.8
Glider	0.012-0.015	0.8-0.9
Remote controlled	0.025-0.045	0.75-0.85

From Table 3, the ABT-18 UAV belongs to the group of ‘small GA with fixed landing gear’, hence, *e* is 0.65 to 0.8. Therefore, considering the minimum value for *e* is 0.65. Hence:

$$K = \frac{1}{3.142 \times 4.8 \times 0.65} = 0.10201$$

Thus, the lift induced drag for the aircraft is:

$$C_{Di} = 0.10201 C_L^2$$

Hence, the drag polar of ABT-18 UAV from Equation 1 is given as:

$$C_D = 0.0384 + 0.10201 C_L^2$$

From the results presented, it has been revealed that the induced drag of an aircraft is affected by the aspect ratio (AR) of the wing and the Oswald efficiency (e). It can be observed that the drag contributed by the wing, $C_{D0w} = 0.011$ to the total drag is higher than that contributed by the fuselage, $C_{D0f} = 0.00842$ and a similar trend can be seen in Bajaj, (2019). Thus, the wing of the ABT-18 UAV presented the most drag input due to its high cross-sectional area. The drag polar estimated for ABT-18 UAV is presented as $C_D = 0.0384 + 0.10201 C_L^2$.

4. CONCLUSION

This study successfully estimated the drag polar of the ABT-18 UAV. In estimating the drag contributions made by each part of the UAV to different types of drag, it was found out that the wing of the ABT-18 UAV presented the most drag input due to its high cross-sectional area.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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