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DEVELOPMENT OF A PARAMETERIZED DRAG MODEL FOR ROTORCRAFT

by

Ali Mhowwala

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I would love to take this opportunity to express my gratitude to all those without whom it would not have been possible to complete my degree let alone this project.

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May 8, 2020

ABSTRACT

DEVELOPMENT OF A PARAMETERIZED
DRAG MODEL FOR ROTORCRAFT

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The University of Texas at Arlington, 2020

Faculty Mentor: Dudley E. Smith

Drag estimation is of significant value in the design of any aircraft, whether it may be fixed wing or rotorcraft. Drag has a heavy influence on the aircraft's performance including its lift, which in turn impacts the aircraft's geometry, weight, and amount of fuel required. In the design process where several configurations are tested for their performance to meet the mission requirements in the most optimum way, it is not feasible economically nor an efficient use of time to create a wind tunnel or computational fluid dynamic analysis to find the drag.

This report explores the implementation of an age-old component buildup method of drag calculation in a parametric computer-based MATLAB model to find the drag for a FARA rotorcraft configuration. The issue with component buildup is that it is cumbersome. However, with the advent of computation and programming, it is ideal to create a modular program for drag calculation.

The categories of bodies of revolution and lifting surfaces used in component buildup can be directly implemented into MATLAB to create a versatile program, which can account for varying configurations of preliminary designs, as well as calculate drag to a fraction of a second. This report demonstrates the implementation of this technique and calculates the drag of the co-ax configuration assigned to the honors group in the senior design project.

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CHAPTER 1

INTRODUCTION

1.1 Project Objective

In the two-semester senior project for Bachelor of Science in Aerospace Engineering under the guidance of Dr. Dudley Smith, the students were tasked with developing a conceptual and preliminary design for the U.S Army's capstone Future Attack Reconnaissance Aircraft (FARA) program.

1.1.1 FARA Specifications

The army sought a vehicle capable of reconnaissance as well as light attack missions. The requirements proposed by the army in the RFP include a vehicle footprint of 40 X 48 ft, the capability to hold eight hellfire missiles, capacity for two pilots, as well as the ability to reach a threshold speed of 170 knots and a target speed of 200+ knots. The rotorcraft (helicopter) also needed to be lightweight, have low rotor tip speed to limit acoustic signature, and be streamlined to operate on a limited single engine power supply of 3000 hp (uninstalled) [1].

1.1.2 Project Progress

The class was divided into four groups with different rotorcraft configurations. The honors group was given the compound coaxial configuration. My role in the team was that of the Aerodynamics, Systems and CAD Engineer. As an aerodynamics engineer, my responsibilities included overviewing and calculating the performance of the rotorcraft which included drag, lift, gross/empty weight, etc. My major responsibility was to create and implement the drag model for the rotorcraft which would be the core of the synthesis code. Last semester a preliminary configuration for the rotorcraft was selected and initial sizing for it was completed. The goal of this semester was to further refine the preliminary design obtained last semester and to develop a synthesis code to determine the best configuration to satisfy the mission requirements.

1.2 Significance of Drag and Parametric Model

The drag is the resistance offered to the motion of a vehicle by the medium in which it travels. Calculation of drag of an aircraft/rotorcraft is a crucial topic in aerospace since it has the highest impact on the performance of any aircraft. The drag impacts the lift capabilities, weight, fuel requirements, and structural design. It would be sufficient to say the drag of an aircraft is of utmost importance when finalizing its design. Now as important as it is, calculation of drag is a cumbersome process and calculating it manually with each configuration is not feasible due to time limitations.

To come up with the most optimum designs, several configurations need to be analyzed during the synthesis phase and due to their varying geometry, the difference in their aerodynamic and friction drag would be substantial. Therefore, if a parametric component-based model for drag calculation could be developed, it would streamline the design process since the task of calculating drag would be automated for the various configurations. Each configuration would be analyzed by their integral components there and the differences between them could be iterated on a base design to calculate the final drag for each configuration. This would also be very beneficial for modeling and simulation of the final performance properties not only of the rotorcraft for the FARA project but for any rotorcraft in general.

CHAPTER 2

METHODOLOGY

2.1 Component Buildup Overview

The drag of any aircraft/rotorcraft is primarily composed of two components, aerodynamic pressure drag (frontal drag) and friction drag (viscous drag). The aerodynamic drag is due to the movement of the craft against stationary air and the resulting resistance to it. On the other hand, the friction drag is generated due to the viscous effects of the air and the shear forces generated on the aircraft surface opposite to the motion due to that. In the classic conventional technique, the drag of an aircraft is calculated as a quantity called equivalent flat plate drag (*fe)*. It is the representation of drag of an aircraft in terms of an equivalent flat pate with same drag. It has the units of length squared and is just a function of aircraft design and is independent of flight conditions. This quantity is later scaled according to atmospheric and flight conditions to find the total drag [2].

The methodology used in this project to calculate the *fe* is called the component build-up method. Since the eventual goal was to create a parametric computer-based drag calculation model and program, component build-up method for drag calculation is most ideal because, in it, the individual components of the aircraft (fuselage, rotors, nacelles, tails, lifting surfaces, etc.) are classified into different categories [3]. Drag is calculated according to their respective models via the process of finding friction and pressure drag for each of them and subsequently combining the result to calculate the total drag of the craft [5].

This technique enabled the creation of a modular algorithm which could be applied to analyze the various rotorcraft configurations of the FARA project and calculate each configuration's drag respectively. This technique streamlined the synthesis process since for each new configuration to be analyzed, the components simply needed to be added or removed for drag calculations instead of needing to calculate the drag of the entire rotorcraft geometry as done in CFD or Wind tunnel methods, which are time-consuming and expensive. For this project, the drag model operated at FARA cruise conditions, 4k 95 at the velocity of 170 knots and utilized the following categories of models to calculate the component drags. The co-ax configuration on which the model operated is shown in the figure below. The model was then incorporated into a MATLAB code to parametrize it according to its input geometry. The input geometry was imported from CAD and sizing calculations.

Figure 2.1: Final render of compound co-ax configuration

2.2 Bodies of Revolution

Drag of the majority of the rotorcraft components were modelled under this subcategory. Bodies of revolution include the fuselage, hubs, ducted fan shroud, flir ball, and gun.

In order to calculate drag under the bodies of revolution, fineness ratio, hydraulic diameter, frontal area and wetted area of the components are used to find the pressure (frontal) and parasitic (skin friction/viscous) drags, which are then averaged to find the total drag of the component. For some components like fuselage, pylon, flir ball and gun, the coefficient of skin friction drag can be found directly by utilizing the Reynold's number [6].

The frontal area (2D projected area of the body facing the flow direction) was then used to find the hydraulic diameter (diameter assuming frontal area as that of an equivalent circle) of these components, and thus the fineness ratio of the aircraft (ratio of length and hydraulic diameter of the component). The ratios for frontal drag (pressure drag) and wetted drag (friction drag) coefficients to coefficient of skin friction were then calculated [7]. For each component, the net wetted area was then measured using the models and scaled accounting for interferences.

The frontal and wetted areas, along with C_{Df}, C_{Dwet}, from the above calculations were used to calculate the pressure drag and friction drag. The average of these two was taken to determine the drag of the component.

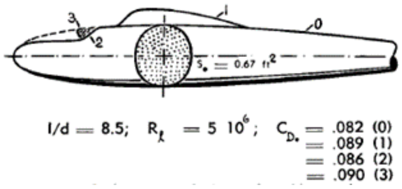


Figure 2.2: Figure showing frontal area of aircraft fuselage [4]

For other components (ducted fan shroud, hubs) the same technique was used to calculate drag, along with some modifications, for example, like to account for the hub fairing geometry. Drag coefficients for some components were obtained from certain sources like the contractor's report [8] for the shroud. Certain corrections for thickness were also considered. These drag values were then, in the end, converted to the flat plate equivalent drag (*fe*).

2.3 Lifting Surfaces

The wing used to offload thrust, as well as the mast which had a fairing to reduce drag, were modelled for drag under this category.

To calculate drag using lifting surfaces criteria, the properties of airfoil geometry constituting the wing and mast fairing were used. The reference 2D area (planar area) was calculated using the root chord and taper ratio and was scaled using net wetted area, gross wetted area and thickness. The coefficient of drag was obtained from the airfoil properties from theory of wing sections [9] and was used to calculate drag by scaling through the net wetted and gross wetted area [5].

2.4 Miscellaneous

To calculate the drag that is as close to drag of the aircraft in reality, miscellaneous factors concerning momentum (cooling drag), exhaust plume drag, roughness and leakage were considered. These were calculated as the fraction of the subtotal fe of the components, as well as engine IRP, for the momentum drag. These factors were obtained from Contractor's report [8] and Methods for drag estimation Jan Roskam (P 3.70) [4].

CHAPTER 3

ANALYSIS

The entire co-ax configuration of the rotorcraft was broken into individual components and their geometries obtained from their respective solid models were sent to a parametric MATLAB code implementing the component build up in order to calculate their respective equivalent flat plate drags (*fe*) . They were added to find the entire aircraft's *fe* which then could be utilized to find the drag at any flight conditions. To find the *fe,* the model ran on the FARA specified cruise conditions 170 knots speed, 4k feet altitude and a 95 °F temperature [1]. The dynamic pressure at these conditions was found to be 86.44 psf (pounds force).

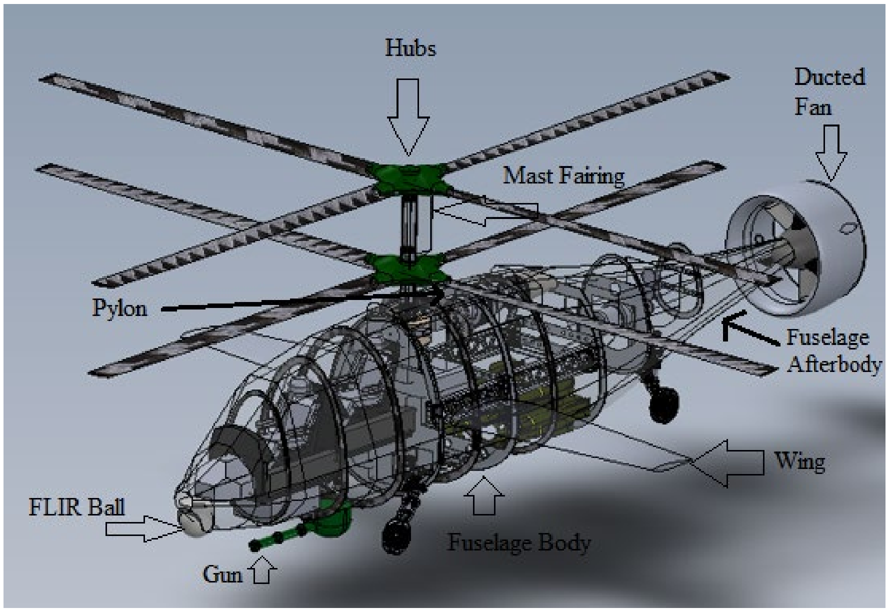


Figure 3.1: Transparent render configuration showing labelled components

3.1 Bodies of Revolution

The majority of the rotorcraft components were modelled under the subcategory of bodies of revolution. These drag calculations were conducted for the fuselage, hubs, ducted fan shroud, flir ball, and gun.

3.1.1 Rotorcraft Fuselage and Afterbody

In any aircraft, whether a fixed wing of an airplane or a rotorcraft like a helicopter, the central body section is called the fuselage [10]. It is the central holding structure which accommodates the crew, passengers, cargo, avionics and other system of the aircraft. Frequently, the fuselage also includes a fuel tank. Therefore, it goes without saying that the fuselage is geometrically the largest component in an aircraft. The drag contribution due to fuselage is subsequently one of the largest in the aircraft. The fuselage drag under the component build up method is modelled as a body of revolution [2][4].

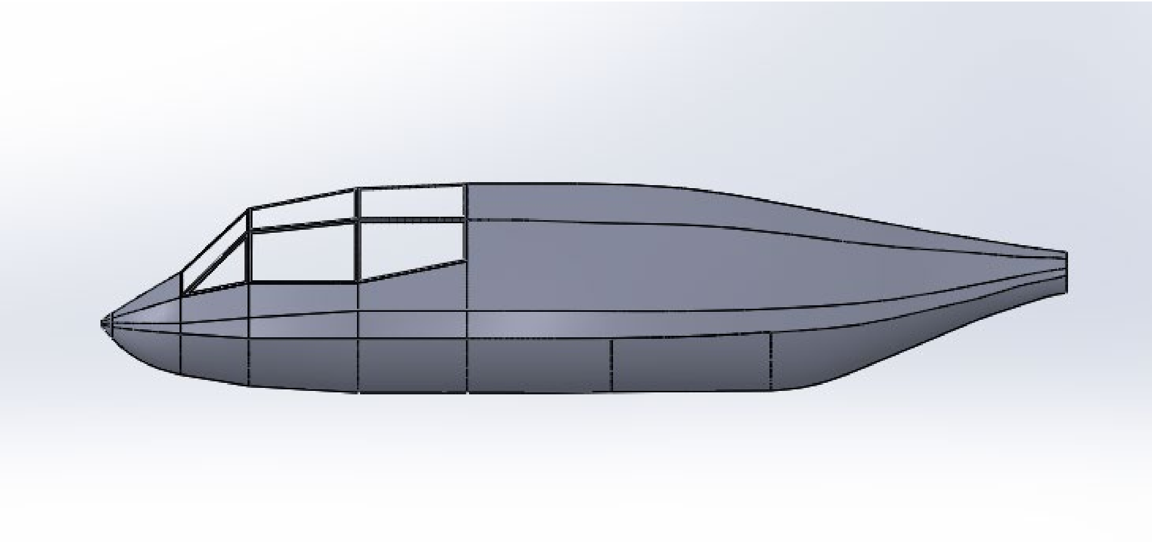


Figure 3.2: Solid model of the rotorcraft fuselage

First the length of the fuselage from the nose to the tail tip was taken and was used along with kinematic viscosity and velocity to find the fuselage Reynolds number according to following equation [7][11]:

$$R_e = \frac{VL}{\nu} \qquad \text{(eq 1)}$$

The Reynolds number is then used to find the skin friction coefficient using [6]:

$$C_{Fb} = \frac{0.455}{(\log_{10} R_e)^{2.58}} \qquad \text{(eq 2)}$$

The frontal area of the fuselage is used to find the hydraulic diameter which is then used to find the fineness ratio. This ratio along with a non-circular section correction factor (since the fuselage geometry is not perfectly circular), typically 0.05 for helicopters, is used to find the 3-D correction factor (which accounts for both frontal and viscous drag) according to the following equation [8]:

$$k_{3-D} = 0.001\left(\frac{l}{d}\right) + 1.5\left(\frac{d}{l}\right)^{3/2} + 8.4\left(\frac{d}{l}\right)^{3} + C \qquad \text{(eq 3)}$$

The 3-D correction factor, interference factor (due to interference with other bodies, typically 1.2 times drag of wing and pylon), and wetted area (from geometry) is used to find the equivalent flat plate drag of the fuselage using following equation:

$$f_e = C_f A_w (1 + k_{3-D}) I \qquad \text{(eq 4)[8]}$$

Fuselage afterbody drag for the fuselage will be calculated separately since the fuselage is connected to the ducted fan in this configuration. For this calculation, the afterbody fore cross section area was used to find the hydraulic diameter, along with the length to find contraction ratio. Finally, the contraction ratio and fore cross section area were used to find the afterbody flat plate drag according to following equation [8]:

$$f_e = 0.008\left[6\left(\frac{de}{le}\right)^{\frac{5}{2}} - 1\right] Ao \qquad \text{(eq 5)}$$

In this equation, d_e, l_e, and A_o are the diameter, lengths, and area respectively. This drag is combined with the fuselage *fe* to find the total flat plate equivalent drag of fuselage/ afterbody combination. In our case, this calculation came out to be 3.747 ft^2.

3.1.2 Rotor Hubs

In a rotorcraft, a hub is the portion of a rotor that holds the blades used for vertical lift (hovering) and forward flight. Hubs constitute a major portion of drag of any rotorcraft as they are non-streamlined due to the pitch links and controls for the blades that stick out in the airflow. In our case, it was especially significant since in a co-ax configuration, there were two rotors and thus the hub drag was twice than that of a conventional rotorcraft.

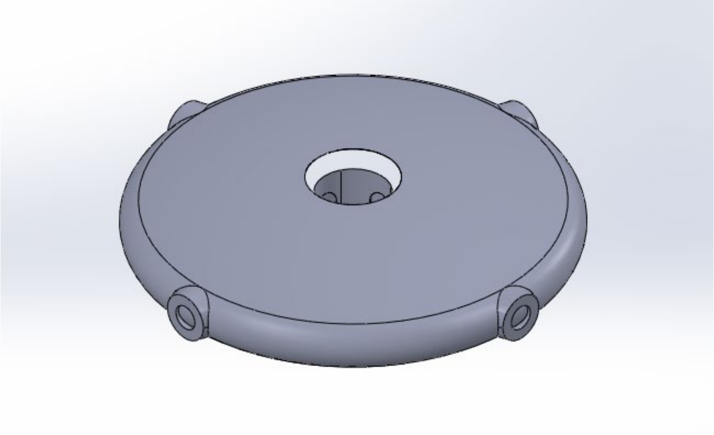


Figure 3.3: Solid model of rotor hub with faring

In our configuration, we covered the hubs and controls (pitch links used to change blade angle) with an ellipsoidal fairing to make them more streamlined. This also made it possible to use the body of revolution category of the component buildup method to find their drag [8][12].

In case of the hubs, the characteristic length used to calculate the Reynolds number using (eq 1) is the hub's diameter which was imported from geometry. Because the hub was covered by an ellipsoidal fairing, to calculate the frontal area and wetted area, formulae for the area of 2-D ellipse as well as surface area of 3-D ellipsoid were utilized respectively [13]. The major and minor diameters along with the height were imported from the geometry [14].

Hydraulic diameter was then calculated using frontal area similar to before and was then used to calculate the fineness ratio. The coefficient of skin friction was then calculated according to (eq 2). The coefficient pf skin friction was then used to calculate the coefficients of pressure and wetted (viscous) drag according to following equations [7]:

$$\frac{C_{Df}}{C_{Fb}} = 3\left(\frac{l}{d}\right) + 4\left(\frac{d}{l}\right)^{1/2} + 21\left(\frac{d}{l}\right)^{2} \tag{eq 6}$$

$$\frac{C_{D_{wet}}}{C_{Fb}} = 1 + 1.5\left(\frac{d}{l}\right)^{3/2} + 7\left(\frac{d}{l}\right)^{3} \tag{eq 7}$$

In this case the *l* and *d* signify the characteristic length and hydraulic diameter of the hub. The ratios shown in the equations were multiplied with the coefficient of skin friction calculated previously to find the corresponding pressure and wetted drag coefficients. C_{Df} and C_{Dwet} were then used to find the gross *fe* by multiplying them with the frontal and wetted area respectively and taking an average [2][7].

$$f_e = \frac{A_f C_{Df} + A_w C_{Dwet}}{2} \tag{eq 8}$$

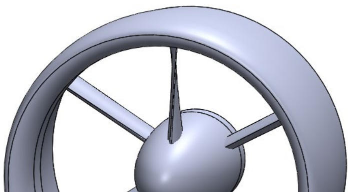
Now to account for non-circularity and 3-D correction, (eq 3) was used to calculate k_{3-D} . An interference factor to account for hub-pylon interference was found to be 1.3 [8]. The final *fe* for both the hubs was then found by using following equation:

$$f_{e\ hubs} = (1 + k_{3-D})(2If_e) \tag{eq 9}$$

In the equation, I is the interference factor and a two is multiplied to determine the total *fe* for both hubs. In our case, the total hub *fe* was found to be 7.961 ft^2.

3.1.3 Ducted Fan Shroud

In the co-ax configuration the group worked, a ducted fan was added to supplement the rotorcraft’s forward thrust to meet the speed specifications given by FARA.



Bell X22-A

Figure 3.4: Ducted fan solid model (left) Bell x22-a with ducted fans (right)

The drag inherent due to the fan will be accounted for in the power/performance calculations, while the drag due to the shroud holding the fan has to be calculated separately. The shroud's drag can be modeled as a body of revolution [7].

To streamline the shroud and therefore reduce its drag, the shroud was modelled with the geometry of an airfoil cross-section. Since it has a complete revolution around the fan axis, it will still be modelled as a body of revolution rather than as a lifting surface. So, in this case, the characteristic length used to calculate the Reynolds number (eq 1) was the shroud airfoil chord and was imported from geometry. The 2D drag coefficient (C_{Df}) was found from the airfoil properties of NACA 0015 [15].

The wetted area was calculated by multiplying the shroud chord with shroud circumference, both of which are imported and calculated from geometry. The frontal area was calculated by multiplying the circumference and thickness of the shroud together. The hydraulic diameter was then calculated using the frontal area as seen in previous sections. The fineness ratio was the ratio between the shroud chord and hydraulic diameter. The equivalent flat plate drag was then found using (eq 4). In the case of shroud, the frontal drag was not significant and therefore only the wetted area was used to find *fe*. The *fe* was found to be 0.2545 ft^2.

3.1.4 Rotor Pylon

In a rotorcraft, a pylon is a structure below the rotor blades that houses the engine intake, as well as bearings to hold the rotor shaft in place.

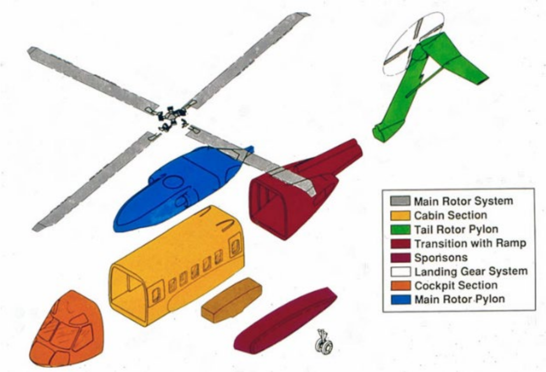


Figure 3.5: Diagram showing pylon and other components [16]

The pylon has a geometry which does not completely blend into the fuselage like the cockpit and therefore has to be modelled separately for drag. It can be modelled as a body of revolution [8].

For the pylon, the characteristic length, frontal area, wetted area was obtained from the CAD model and directly imported into the MATLAB code. The hydraulic diameter was then calculated from frontal area in the manner previously seen. The Reynolds number was then determined from these geometries by using (eq 1). The fineness ratio was found by dividing the characteristic length by the hydraulic diameter.

The coefficient of skin friction was then calculated from (eq 2). The ratios of coefficients of pressure and friction drag to skin friction drag were calculated using (eq 6 and 7). These ratios were then multiplied with the coefficient of skin friction calculated previously to find corresponding pressure and wetted drag coefficients. C_{Df} and C_{Dwet} were then used to find the gross fe by multiplying them with the frontal and wetted area respectively and taking an average as seen in calculations before using (eq 8) [2][7].

Equation 3 was then used to calculate $k_{3\text{-}D}$ to consider factors for 3-D correction and non-circularity. The interference factor to account for the fuselage and mast interference was found to be 1.2 [8]. The final equivalent flat plate drag was found by using (eq 9) without multiplying *I* (correction factor) by two since it was done only for hubs. Finally, the total pylon *fe* was found to be 0.177 ft^2.

3.1.5 FLIR Ball

The avionics and sensor package prescribed by FARA included a FLIR (Forward Looking Infrared Camera) ball that was fitted to the nose of the rotorcraft.

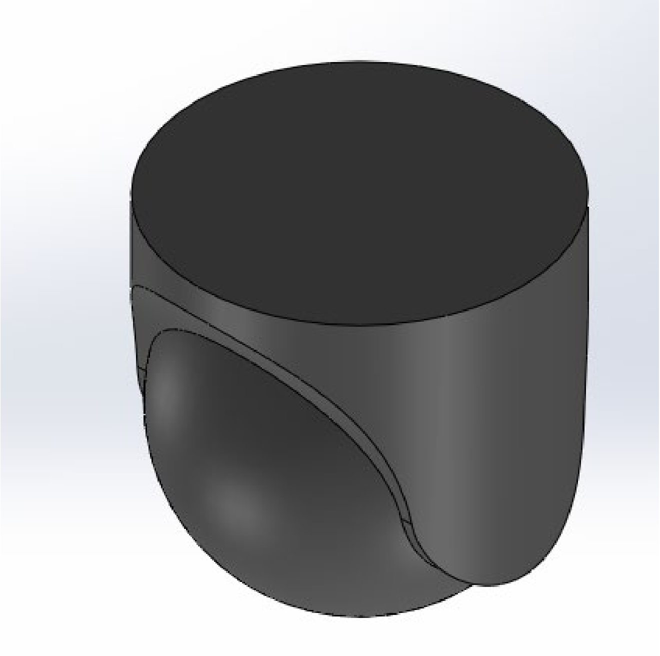


Figure 3.6: Solid model of FLIR ball assembly

Since the FLIR ball was protruding from the fuselage body, its drag could not be modelled with it and therefore had to be modelled separately. Since it is a spherical object, its drag can be approximated as such under the component buildup method [7].

The FLIR ball diameter was imported from the CAD geometry. The frontal area was calculated to be the area of the circle since the ball is spherical. Similarly, wetted surface area was calculated using the surface area equation for a sphere. In this case, the hydraulic diameter is equal to the diameter of the ball. The ball diameter is also its characteristic length and is used with (eq 1) to calculate Reynolds no. Since the diameter and hydraulic diameter are same, the fineness ratio for FLIR ball is one.

The skin friction drag coefficient is then calculated using (eq 2). The ratios of coefficients of pressure and friction drag to skin friction drag were calculated using (eq 6 and 7) as done before. The ratios were then converted to their respective pressure and wetted drag coefficients using the skin friction drag calculated earlier. C_{Df} and C_{Dwet} were used to find the gross *fe* by multiplying them with the frontal and wetted area respectively and taking an average as done previously using (eq 8) [2][7].

The final *fe* was found by scaling the gross *fe* by an interference factor of 1.2 obtained from [8] to account for fuselage interference with the FLIR ball. In the end, the total *fe* of FLIR ball was found to be 0.6738 ft^2.

3.1.6 Gun

The FARA RFP (Request for Proposal) required the rotorcraft to be mounted with a XM301 20mm Lightweight Gatling Gun. In order to avoid interference with the FLIR thermal imaging, the gun was mounted on the belly (lower portion) of the rotorcraft.

Figure 3.7: XM301 20mm lightweight Gatling gun with ammo

The gun was one of the components of the configuration which was sticking out in the flow apart from the hubs and therefore expected to be one of the major contributors to the overall rotorcraft drag. The gun too can be modelled as a body of revolution [7]. The drag of the gun itself was modelled as two separate components, the gun barrel and the mount fairing, which contained the holding as well as the actuating mechanism.

3.1.6.1 Gun Barrel Drag

The diameter and length of the barrel were obtained from the XM-301-gun properties [17]. The hydraulic diameter is equal to the diameter. The fineness ratio was found by dividing the barrel length by diameter. The frontal area was found by approximating the barrel cross section as a circle and calculating its area using the diameter. The wetted surface area was calculated using the diameter and length by approximating the barrel as a single cylinder.

The Reynold's number was calculated taking the barrel's length as the characteristic length and using (eq 1). The coefficient of skin friction was then calculated using (eq 2) similar to as done previously. The ratios of the coefficients of pressure and friction drag to skin friction drag were calculated using (eq 6 and 7).

These ratios were then multiplied with skin friction coefficients to find the respective frontal and viscous drag coefficients. Gross *fe* was then obtained using through the coefficients and areas (eq 8) . 3-D Effects correction factor $k_{3\text{-}D}$ was the found using fineness ratio and (eq 3). The interference factor to account for fuselage was found in the contractor's report [8] to be 1.4. The final equivalent flat plate drag was found by using (eq 9) but without multiplying I (correction factor) by two since it was done for hubs.

3.1.6.2 Gun Mount Fairing Drag

The fairing was approximated as a spherical body and therefore as in the case of the FLIR ball in section 3.1.5 the frontal and wetted surface area were calculated as those of a sphere from the diameter imported from the geometry. As, in the previously seen case, the hydraulic diameter is equal to the diameter. The length of the fairing that is also the diameter is used to calculate the Reynolds no using (eq 1).

The fineness ratio of the fairing was found to be 1 due to equal length and diameter. The coefficient of skin friction was then found using (eq 2). The ratios of coefficients of pressure and friction drag to skin friction drag were again calculated using (eq 6 and 7). These ratios were multiplied with the coefficient of skin friction calculated before to find corresponding pressure and wetted drag coefficients for the gun fairing.

Gross *fe* was then calculated using the coefficients and areas (eq 8) . 3-D Effects correction factor $k_{3\text{-}D}$ for fairing was found using fineness ratio and (eq 3). The interference factor to account for fuselage was obtained from [8] was again found to be 1.4. The final equivalent flat plate drag for fairing was calculated by using (eq 9), but without multiplying I (correction factor) by two since it was done for the hubs.

The total *fe* for gun was found by adding the barrel and fairing *fe*. Using the MATLAB code, it was found to be 2.227 ft^2.

3.2 Lifting Surfaces

The wings and other components of an aircraft having an airfoil section are usually modelled separately from bodies of revolution because they have aerodynamic characteristics which are significantly affect their drag performance. In the co-ax configuration used, the wing used for offloading thrust and the rotor mast that had a fairing to reduce the drag were modelled under this category.

3.2.1 Rotor Mast with Fairing

The mast holding the rotor configuration is cylindrical and hence leaving it as it is in the incoming airflow will result in a significant drag that will heavily affect the helicopter's performance. Therefore, an airfoil shaped faring was attached around the mast using a bearing, to cover the mast and surrounding pitch links. The aerodynamically streamlined characteristics of airfoil would reduce the drag by a considerable amount.

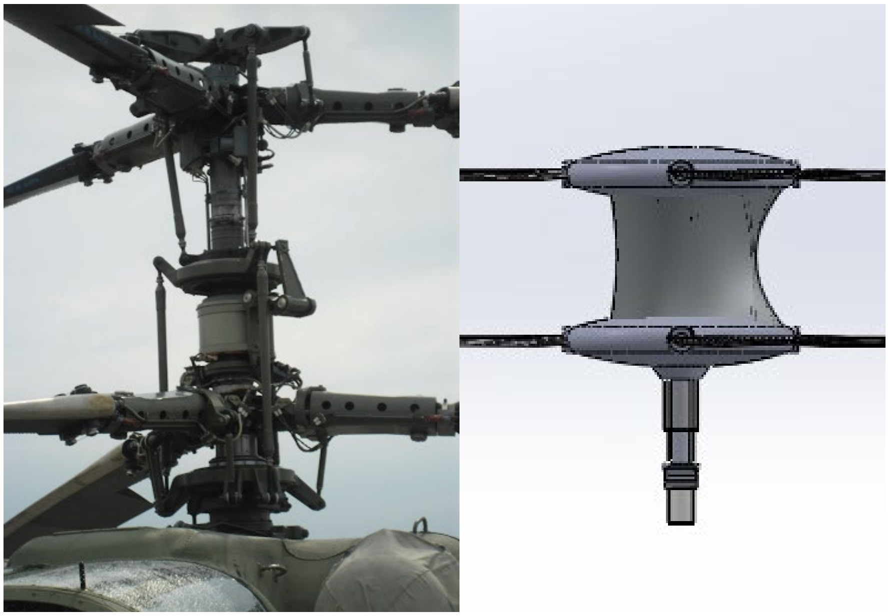


Figure 3.8: Exposed mast (Kamov KA-52) (left), configuration with faring (right)

The airfoil used for the fairing was NACA 0012 airfoil [9] which is a symmetrical, uncambered airfoil. The drag and hence equivalent flat plate drag (*fe*) can be calculated using following equation [2][3]:

$$D = q_{\infty} S C_d \frac{S_{wet\,net}}{S_{wet\,gross}} \qquad \text{(eq 10)}$$

The drag can be converted to *fe* by dividing by dynamic pressure. The faring height and diameter were imported from the geometry. They depended on the geometry of the mast. The chord length of the fairing was 12 percent of its diameter which is a property of NACA 0012 airfoil [9]. The fairing wetted area was calculated by multiplying the fairing chord length with height. Frontal area was then calculated by multiplying the diameter by height and was used to calculate the fineness ratio which was the chord length divided by the hydraulic diameter (calculated from frontal area like in previous sections).

In our case, the net wetted area and gross wetted area are the same and therefore the ratio shown in (eq 10) is 1. The C_d (Coefficient of drag) was obtained from NACA 0012 airfoil properties [9]. Since the C_d obtained was for a 2D airfoil, a 3-D correction factor was therefore calculated using fineness ratio and (eq 3). The non-circular correction C used in (eq 3) is zero. The mast interference factor to account for hubs was found to be 1.2 [8][7].

The gross fe calculated by dividing drag obtained from (eq 10) was then scaled using correction factors calculated above and (eq 9) to find the total fe of the fairing. It is to be noted that like previous non-hub cases, the 2 in the equation in front of interference factor I will be dropped. Finally, the total fe for the mast fairing was calculated to be 0.937 ft^2.

3.2.2 Wing

The wing is used to offload thrust, generated lift and was therefore also modelled as a lifting surface to determine drag under the component buildup method.

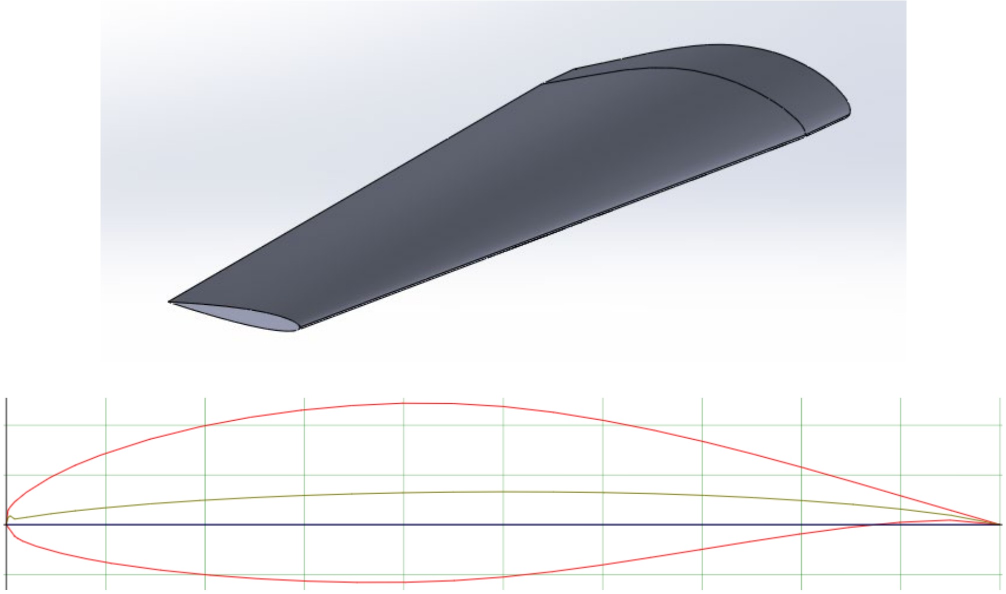


Figure 3.9: Solid model of wing (top), airfoil cross section (bottom)

The airfoil used for the wing was six-digit NACA 6_{53}-618. It had a low profile drag as well as gentle trailing edge stall characteristics which reduced its drag footprint [9]. For our configuration, the wing was designed taking only exposed area into this configuration. As a result, like previously, the ratio of gross to net wetted area in (eq 10) would be 1.

The drag coefficient for airfoil C_d was found to be 0.011 [9]. Since this was a non-symmetric airfoil, the wetted area was calculated by the solid modelling software and imported in the drag model as a geometry value. The wing drag was then calculated using (eq 10) and divided by the dynamic pressure to find *fe*. The *fe* was then multiplied by an interference factor of 1.2 [8] to account for fuselage interference. The final *fe* for the wing was found to be 1.917 ft^2.

3.3 Miscellaneous

The accurate determination of drag requires accounting for miscellaneous factors not included in regular categories of component build up. Usually, they require a lot of bookkeeping of surface and configuration details but can be accounted for by a good degree using some factors.

3.3.1 Momentum (Cooling Drag)

This drag is a result of the loss in momentum of air as it enters and exits the cooling system of the hydraulic power supply, engines, transmission. Losses also occur due to air entering the heating and ventilation systems of the rotorcraft [8]. The procedure of estimating momentum drag can be simplified and calculated using the following equation which is a function of the cooling system design factor and installed shaft horsepower available.

$$f_e = 2.5 \times 10^{-5}(SHP_{inst})k_c) \qquad \text{(eq 11)}$$

The value for SHP_{inst} was imported from the propulsion module of the design synthesis code whereas value for k_c was selected to be 6, a maximum given in [8]. Using (eq 11) given above, *fe* for cooling momentum drag was determined to be 0.364 ft^2.

3.3.2 Roughness and Leakage

Roughness drag includes surface irregularities such as rivet heads, seams, waviness in the skin, etc. Leakage drag results from air that enters or exits the fuselage around cowlings, access doors, windows, etc. These two can be accounted by taking a percentage of the subtotal drag (*fe*) found by adding all the previously calculated *fe* under the body of revolution, lifting surfaces and cooling momentum drag. For a good estimate in preliminary design, it is taken as 5 percent of the subtotal *fe* [8]. Following the above procedure, *fe* for roughness and leakage was calculated to be 0.963 ft^2.

3.3.3 Protuberance and Exhaust

Protuberances are represented by larger external items such as antennas, vents, drains and anti-collision lights on a rotorcraft. In the absence of a detailed design, the protuberances are accounted for by takin 5 to 10 percent of the aircraft's subtotal drag [8][4]. In our case we took 10 percent of the subtotal drag (calculated as shown in previous section). The *fe* for perturbance was calculated to be 1.926 ft^2.

In case of turboshaft installations, the engines provide a net thrust at speeds up to 140 to 150 knots. At higher speeds, an additional drag due to exhaust modifications exists which can be omitted for slower speeds. Since our rotorcraft cruises at 170 knots and has dash speeds of up to 200 knots+, this factor needs to be accounted [8]. The *fe* for exhaust drag (engine momentum drag) was calculated from the figure below and was found to be equal to 1.

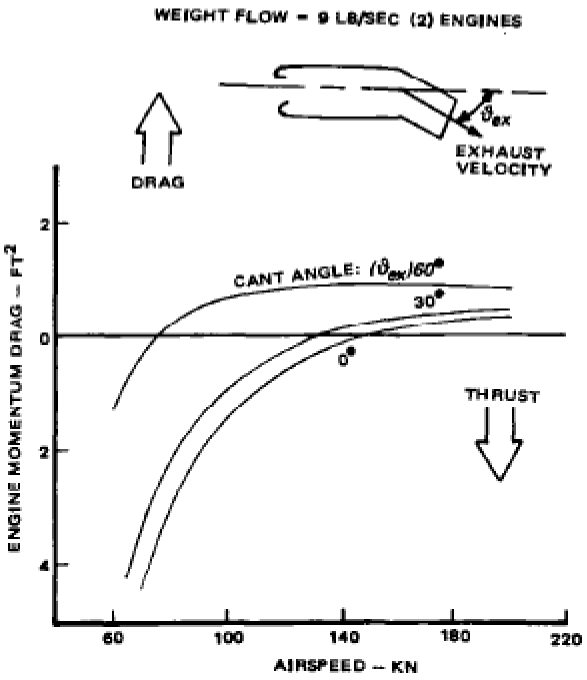


Figure 3.10: Example of engine momentum (exhaust) drag [8]

CHAPTER 4

CONCLUSION

The component buildup method for drag calculation was successfully implemented in creating a parametric model to determine the equivalent flat plate drag of the compound co-ax rotor configuration. The resulting program developed was modular with capability to add or remove parts in the rotorcraft with automatically considering the interference factors involved. The program run time was less than a minute which is a fraction of what other drag estimation methods take and provided highly accurate results for the total drag of the rotorcraft.

4.1 Total Drag

When the model was run, the algorithm based on component buildup calculated equivalent flat plate drags (*fe*) of components falling under bodies of revolution, lifting surfaces as well as miscellaneous category. These individual *fe* were then added together to find the total equivalent flat plate drag of the helicopter. The total *fe* of the rotorcraft was calculated to be 22.1495 ft^2. The drag force in lbs calculated at the cruise condition of 4k 95 at the velocity of 170 knots was then found by multiplying the *fe* by dynamic pressure and was determined to be 1914.599 lbs.

4.2 Drag Breakdown

The drag breakdown for individual components of the rotor craft is summarized below in table 4.1. It is displayed as a percentage of total drag in figure 4.1 for better visualization.

Table 4.1: Drag Summary

Component	Modelled as	Equivalent Flat plate drag (fe) [ft^2]
Fuselage	Body of revolution	3.747302155
Hubs	Body of revolution	7.961479546
Wing	Lifting surfaces	1.917365504
Ducted Fan	Body of revolution	0.254469005
Pylon	Body of revolution	0.17735904
Mast	Lifting surfaces (added faring)	0.937178605
FLIR Ball	Body of revolution	0.673795741
Gun	Body of revolution	2.227492143
Momentum	Cooling drag	0.363953001
Exhaust	Miscellaneous	1
Subtotal		19.26039474
Roughness	Miscellaneous	0.963019737
Proturbance	Miscellaneous	1.926039474
Total		22.14945395

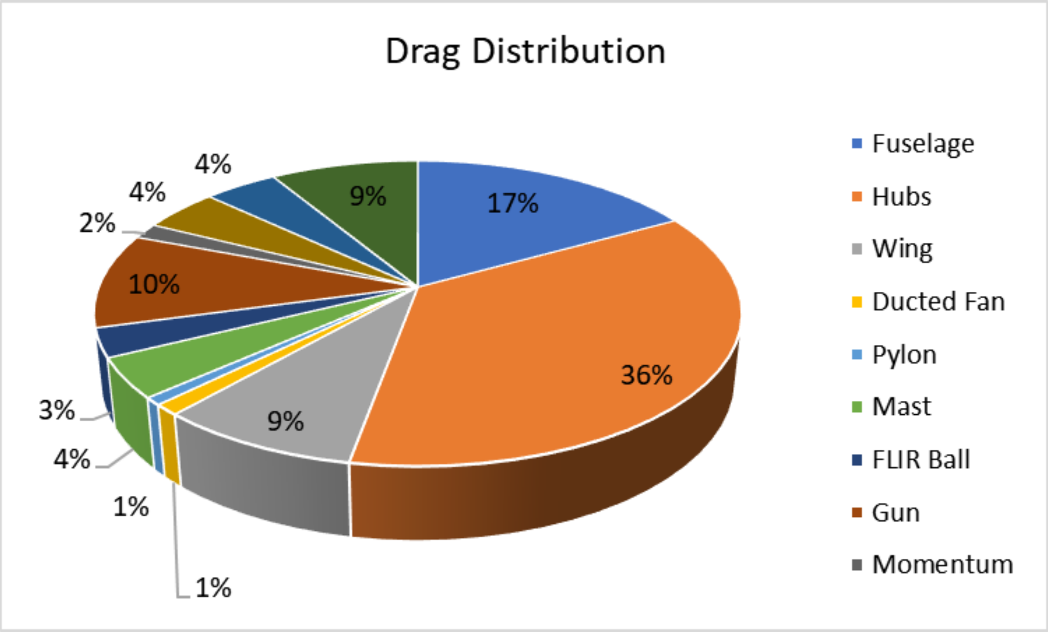


Figure 4.1: Drag breakdown

4.3 Reasoning

From the drag distribution shown in figure 4.1, it can be seen that the majority of the rotorcraft drag is due to hubs and fuselage followed by gun and wings. This is not surprising and was expected as the major drag contribution for any rotorcraft is due to its hubs and fuselage. As predicted the hubs, gun and wing have the highest contribution since they are sticking out in the airflow when the helicopter is in forward motion, while the drag of fuselage is high since it has the largest area. The drag performance was comparatively good for the complex configuration used and enabled the team to not only meet but exceed the performance criteria specified by FARA [1].

APPENDIX A

PARAMETRIC MATLAB CODE

```
function [fe] = DragModel_v4(alt,V,geom)
%{
Coaxial Compound Configuration FARA Entry
Drag Model (Component Build-Up)
Objective: Use the analytical component build-up model to estimate the
flate plate equivalent drag area fe
%}

%% Ambient Properties
[atmos] = usstdatmos(alt);
rho = atmos.rho;                                          %Density [slug/ft^3]
kin_visc = atmos.kinvisc;                                    %Kinematic Viscosity [ft^2/sec]

%% Flight Conditions
V = V*1.68781;                                            %Conversion from ktas to ft/sec
q = 0.5*rho*V^2;                                          %Freestream Dynamic Pressure
[psf]

%% Component Build-Up
%% Fuselage
%Main Body
% k = 1.2*10^-3;                                            %Surface Roughness Factor
(Rotary Wing Aerodynamics Vol. 2 Chapter 3, section 2.1, pg. 63)
L_fuse = geom.Lfuse;                                        %Fuselage Length [ft]
Re_fuse = V*L_fuse/kin_visc;                                   %Fuselage Reynolds Number
(Used with Fig. 3.2 in Rotary Wing Aerodynamics Vol. 2 for Cf)
% grain = k/L_fuse;                                         %Relative Grain Size [1/ft] (Used
with Fig. 3.2 in Rotary Wing Aerodynamics Vol. 2 for Cf)
Cf_fuse = 0.455/log10(Re_fuse)^2.58;                              %Skin Friction Coefficient
[] (Fig. 3.2 in Rotary Wing Aerodynamics Vol. 2)
S_fuse = geom.sfuse;                                        %Fuselage Wetted Area [ft^2]
Af_fuse = geom.affuse;                                       %Fuselage Frontal Area [ft^2]
D_hyd_fuse = 2*sqrt(Af_fuse/pi);                                %Fuselage Hydraulic
Diameter [ft^2]
FR_fuse = L_fuse/D_hyd_fuse;                                   %Fuselage Fineness Ratio []
C = 0.05;                                                %Non-Circular Cross Section
Correction Factor []
k3d_fuse = 0.001*FR_fuse+1.5*(1/FR_fuse)^1.5+8.4*(1/FR_fuse)^3+C;        %3-D
Effects Correction Factor []
intf_fuse = 1.2;                                          %Fuselage Interference Factor [] 1.2
times drag of pylon & wing
fe_fuse = Cf_fuse*S_fuse*(1+k3d_fuse)*intf_fuse;

%After Body
A0 = 4200.38/144;                                          %After-Body Fore Cross Section
Area [ft^2]
```

```
de = sqrt(4*A0/pi);                                   %Equivalent After-Body Diameter
[ft]
L_fuseab = 133.78/12;                                  %Length of Fuselage After-Body
[ft]
contr_ab = L_fuseab/de;                                %Fuselage After-Body
Contraction Ratio []
fe_ab = 0.008*(6*(1/contr_ab)^2.5-1)*A0;                    %Fuselage After-Body fe
[ft^2]

fe.fuse = fe_fuse+fe_ab;

%% Hub

hubdia = geom.hubdia;                                  %Hub Center Diameter [ft]
hubh = geom.hubh;                                     %Hub Center Height [ft]
S_hub = 4*pi*((((hubdia/2)^2)^1.6075+2*((hubdia/2)...
   *(hubh/2))^1.6075)/3)^(1/1.6075);                     %Lenticular Hub Fairing
Surface Area [ft^2]
Af_hub = pi*(hubdia/2)*(hubh/2);                          %Hub Frontal Area [ft^2]
(NACA TN 3038)
D_hyd_hub = 2*sqrt(Af_hub/pi);                           %Hub Hydraulic Diameter
[ft]
FR_hub = hubdia/D_hyd_hub;                               %Hub Fineness Ratio []
Re_hub = V*hubdia/kin_visc;                              %Hub Reynold's Number []
Cfb_hub = 0.455/log10(Re_hub)^2.58;                         %Turbulent Solution for
the Skin Friction COefficient []
Cdf_hub = Cfb_hub*(3*FR_hub+4*(1/FR_hub)^0.5+21*(1/FR_hub)^2);          %Hub
Pressure Drag Coefficient []
Cdwet_hub = Cfb_hub*(1+1.5*(1/FR_hub)^1.5+7*(1/FR_hub)^3);             %Hub
Viscous Drag Coefficient []
fe_hub = (Af_hub*Cdf_hub+S_hub*Cdwet_hub)/2;                    %Hub fe

C = 0.05;                                           %Non-Circular Cross Section
Correction Factor []
k3d_hub = 0.001*FR_hub+1.5*(1/FR_hub)^1.5+8.4*(1/FR_hub)^3+C;          %3-D
Effects Correction Factor []
intf_hub = 1.3;                                      %hub-pylon drag inteference factor
Rotary Wing Aerodynamics Vol. 2 pg. 69 (ratio 0.15)
fe.hubs = (1+k3d_hub)*(intf_hub*fe_hub+fe_hub);                  %Total hub/blade
shank fe

%% Wing
%NACA 653-618.
Cd_w = 0.011;                                        %Wing Drag Coefficient (Theory of
Wing Sections, Appendix IV)
Sw = geom.Sw;                                        %Wing Planform Area [ft^2]
```

```
intf_wing = 1.2;                                        %Drag Interference Factor from
Fuselage []
fe.wing = intf_wing*Cd_w*Sw;                                      %Wing fe [ft^2]

%% Vertical Stabilizer

%% Canopy

%% Intake/Exhaust System

%% Ducted Fan
%NACA 0015 Airfoil
%Shroud
c_df = geom.CsDr*geom.dfdia;                                      %Ducted Fan Shroud Chord
[ft]
Re_df = V*c_df/kin_visc;                                      %Ducted Fan Shroud Reynold's
Number [] (Used to calculate Cd with NACA 0015 section data)
Cd_df = 0.009;                                          %Ducted Fan Shroud Drag
Coefficient [] (NACA 0015, ref. Aerodynamic Characteristics of Seven Symmetrical
Airfoil Sections Through 180-Degree Angle of Attack for Use in Aerodynamic Analysis
of Vertical Axis Wind Turbines, pg. 94, Fig. 17)
b_df = pi*geom.dfdia;                                      %Ducted Fan Shroud "wing span"
Considering Shroud as an Infinite Wing [ft]
S_df = c_df*b_df;                                        %Ducted Fan Shroud Wetted Area
[ft^2]
thick_df = 0.15*c_df;                                     %Ducted Fan Shroud Max
Thickness [ft]
Af_df = thick_df*b_df;                                     %Ducted Fan Shroud Frontal
Area [ft^2]
D_hyd_df = 2*sqrt(Af_df/pi);                                      %Ducted Fan Shroud
Hydraulic Diameter [ft]
FR_df = c_df/D_hyd_df;                                       %Ducted Fan Shroud Fineness
Ratio []
% k3d_df =  0.001*FR_df+1.5*(1/FR_df)^1.5+8.4*(1/FR_df)^3;              %3-D Effects
Correction Factor []
fe.ducted_fan = Cd_df*S_df;                                      %Ducted Fan Shroud fe [ft^2]

%% Pylon
Af_pylon = geom.afpylon;                                       %Pylon Frontal Area [ft^2]
S_pylon = geom.spylon;                                       %Pylon Wetted Area [ft^2]
L_pylon = geom.Lpylon;                                       %Pylon Length [ft]
D_hyd_pylon = 2*sqrt(Af_pylon/pi);                                    %Pylon Hydraulic
Diameter [ft]
FR_pylon = L_pylon/D_hyd_pylon;                                     %Pylon Fineness Ratio []
Re_pylon = V*L_pylon/kin_visc;                                     %Pylon Reynold's Number
[]
```

```
Cfb_pylon = 0.455/log10(Re_pylon)^2.58;                    %Turbulent Solution for
the Skin Friction COefficient []
Cdf_pylon = Cfb_pylon*(3*FR_pylon+4*(1/FR_pylon)^0.5+21*(1/FR_pylon)^2);
%Pylon Pressure Drag Coefficient []
Cdwet_pylon = Cfb_pylon*(1+1.5*(1/FR_pylon)^1.5+7*(1/FR_pylon)^3);      %Pylon
Viscous Drag Coefficient []
fe_pylon = (Af_pylon*Cdf_pylon+S_pylon*Cdwet_pylon)/2;               %Pylon fe
C = 0.05;                                            %Non-Circular Cross Section
Correction Factor []
k3d_pylon = 0.001*FR_pylon+1.5*(1/FR_pylon)^1.5+8.4*(1/FR_pylon)^3+C;   %3-D
Effects Correction Factor []
intf_pylon = 1.2;                                      %Pylon Interference Factor []
fe.pylon = fe_pylon*(1+k3d_pylon)*intf_pylon;

%% Mast Fairing
%NACA 0012 Airfoil
Cd0_m = 0.01;                                          %Mast Fairing Drag Coefficient []
(NACA 0012, Theory of Wing Sections)
h_m = geom.hmast;                                        %Mast Fairing Height [ft]
d_m = geom.mastdia;                                      %Mast Fairing Diameter [ft]
c_m = d_m/0.12;                                         %Mast Fairing Chord [ft]
S_m = c_m*h_m;                                           %Mast Fairing Wetted Area [ft^2]
Af_m = d_m*h_m;                                          %Mast Fairing Frontal Area
[ft^2]
D_hyd_m = 2*sqrt(Af_m/pi);                                   %Mast Fairing Hydraulic
Diameter [ft]
FR_m = c_m/D_hyd_m;                                        %Mast Fairing Fineness Ratio
[]
k3d_m = 0.001*FR_m+1.5*(1/FR_m)^1.5+8.4*(1/FR_m)^3;                 %3-D Effects
Correction Factor []
intf_m = 1.2;                                         %Mast Fairing Interference Factor []
fe.mast = intf_m*(1+k3d_m)*Cd0_m*S_m;                               %Mast Fairing fe
[ft^2]

%% FLIR Ball
flirdia = geom.flirdia;                                 %FLIR Ball Diameter [ft]
Af_flir = pi*flirdia^2/4;                                %FLIR Ball Frontal Area [ft^2]
S_flir = 4*pi*(flirdia/2)^2;                              %FLIR Ball Surface Area [ft^2]
D_hyd_flir = flirdia;                                   %FLIR Ball Hydraulic Diameter [ft]
FR_flir = 1;                                          %FLIR Ball Fineness Ratio [] (Sphere)
Re_flir = V*flirdia/kin_visc;                                %FLIR Ball Reynold's Number
[]
Cfb_flir = 0.455/log10(Re_flir)^2.58;                          %Turbulent Solution for the
Skin Friction COefficient []
Cdf_flir = Cfb_flir*(3*FR_flir+4*(1/FR_flir)^0.5+21*(1/FR_flir)^2);      %FLIR Ball
Pressure Drag Coefficient []
```

```
Cdwet_flir = Cfb_flir*(1+1.5*(1/FR_flir)^1.5+7*(1/FR_flir)^3);          %FLIR Ball
Viscous Drag Coefficient []
% k3d_flir = 0.001*FR_flir+1.5*(1/FR_flir)^1.5+8.4*(1/FR_flir)^3;          %3-D Effects
Correction Factor []
intf_flir = 1.2;                                          %FLIR Ball Interference Factor []
fe.flir = intf_flir*(Cdf_flir*Af_flir+Cdwet_flir*S_flir)/2; %FLIR Ball fe [ft^2]


%% Gun
%Gun Barrel
D_gun = 0.19685;                                            %Gun Barrel Diamter [ft] (XM-
301)
L_gun = 61/12;                                              %Gun Barrel Length [ft] (XM-301)
FR_gun = L_gun/D_gun;                                            %Gun Barrel Fineness Ratio []
Af_gun = pi*D_gun^2/4;                                           %Gun Barrel Frontal Area
[ft^2]
S_gun = pi*D_gun*L_gun;                                           %Gun Barrel Surface Area
[ft^2]
Re_gun = V*L_gun/kin_visc;                                        %Gun Barrel Reynold's
Number []
Cfb_gun = 0.455/log10(Re_gun)^2.58;                                  %Turbulent Solution for
the Skin Friction COefficient []
Cdf_gun = Cfb_gun*(3*FR_gun+4*(1/FR_gun)^0.5+21*(1/FR_gun)^2);          %Gun
Barrel Pressure Drag Coefficient []
Cdwet_gun = Cfb_gun*(1+1.5*(1/FR_gun)^1.5+7*(1/FR_gun)^3);             %Gun
Barrel Viscous Drag Coefficient []
k3d_gun = 0.001*FR_gun+1.5*(1/FR_gun)^1.5+8.4*(1/FR_gun)^3;             %3-D
Effects Correction Factor []
intf_gun = 1.4;                                           %Gun Barrel Interference Factor []
fe_gun = intf_gun*(1+k3d_gun)*(Cdf_gun*Af_gun+Cdwet_gun*S_gun)/2;       %Gun
Barrel fe [ft^2]

%Gun Mount Fairing
D_gf = 1;                                             %Gun Fairing Base Diameter [ft]
(Hemisphere)
Af_gf = pi*D_gf^2/4;                                       %Gun Fairing Frontal Area [ft^2]
S_gf = pi*(4/3)*(D_gf/2)^3;                                  %Gun Fairing Surface Area
[ft^2]
D_hyd_gf = 2*sqrt(Af_gf/pi);                                   %Gun Fairing Hydraulic
Diameter [ft]
FR_gf = D_gf/D_hyd_gf;                                       %Gun Fairing Fineness Ratio []
Re_gf = V*D_gf/kin_visc;                                      %Gun Fairing Reynold's
Number []
Cfb_gf = 0.455/log10(Re_gf)^2.58;                               %Turbulent Solution for the
Skin Friction COefficient []
```

```
Cdf_gf = Cfb_gf*(3*FR_gf+4*(1/FR_gf)^0.5+21*(1/FR_gf)^2);            %Gun Barrel
Pressure Drag Coefficient []
Cdwet_gf = Cfb_gf*(1+1.5*(1/FR_gf)^1.5+7*(1/FR_gf)^3);               %Gun Barrel
Viscous Drag Coefficient []
k3d_gf = 0.001*FR_gf+1.5*(1/FR_gf)^1.5+8.4*(1/FR_gf)^3;              %3-D Effects
Correction Factor []
intf_gf = 1.4;                                      %Gun Barrel Interference Factor []
fe_gf = intf_gf*(1+k3d_gf)*(Cdf_gf*Af_gf+Cdwet_gf*S_gf)/2;           %Gun Barrel fe
[ft^2]

fe.gun = fe_gun+fe_gf;                                   %Total fe for gun [ft^2]

%% Momentum/Cooling Drag
[~,eng_corr] = eng_perf_v2(alt,0);
SHP_inst = 0.98*eng_corr.IRP;                               %HP Available at Altitude
[HP]
kc = 6;                                             %Cooling System Design Factor []
fe.momentum = (2.5e-5)*SHP_inst*kc;                              %Momentum and cooling
fe (Rotary Wing Aerodynamics, pg. 73)

%% Exhaust Plume Drag
fe.exhaust = 1.0;                                      %Exhaust Plume fe (Rotary Wing
Aerodynamics Vol. 2, Figure 3.11)

%% Miscellaneous Items
%Roughness and Leakage
fe.subtotal =
fe.fuse+fe.hubs+fe.wing+fe.ducted_fan+fe.pylon+fe.mast+fe.flir+fe.gun+fe.momentum+
fe.exhaust;
fe.rough = 0.05*fe.subtotal;                              %Roughness and Leakage
Component [ft^2] (Rotary Wing Aerodynamics, pg. 72)
fe.proturb = 0.1*fe.subtotal;                             %Proturbances "Dirty"
Components [ft^2] (Rotary Wing Aerodynamics, pg. 72)

%% Total fe
fe.total = fe.subtotal+fe.rough+fe.proturb;                      %Configuration Total fe
[ft^2]

end
```

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BIOGRAPHICAL INFORMATION

Ali Mhowwala is earning his Honors Bachelor of Science in Mechanical and Aerospace Engineering from the University of Texas at Arlington in the summer of 2020. He believes in finding a multi-targeted approach to solve modern engineering problems efficiently. To advance his knowledge, he pursued a wide academic curriculum in terms of a double degree and also worked on several research projects including the most recent one with his mentor Dr. Dudley Smith. Dr. Smith inspired Ali to pursue a career in design and controls and therefore after graduation, he intends to pursue graduate education to further strengthen his technical skills. Ali intends to work in developing the next generation of electric UAVs upon completing his education. Currently, he is dedicated to gaining more knowledge as well as experience in industry and academia.