UNIVERSITY OF COLORADO - BOULDER

ASEN 2004

ASEN 2004 Lab 1: Glider - Spring 2020

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Nomenclature

L/D = Ratio of Lift to Drag
C_{D0} = Coefficient of Drag When Lift is Zero
C_L = Coefficient of Lift
α = Angle of Attack
$\alpha_{L=0}$ = Angle of Attack when Lift is Zero
GTOW = Gross Takeoff Weight

Equations

$$C_{D0} = kC_L^2 \tag{1}$$

$$3C_{D0} = kC_L^2 \tag{2}$$

$$C_L = a(\alpha - \alpha_L = 0) \tag{3}$$

$$k = 1/(\pi * e_0 * AR) \tag{4}$$

$$C_D = C_{D0} + kC_L^2 \tag{5}$$

$$C_D = C_{Dmin} + k_1(C_L - C_{LminD}) \tag{6}$$

$$C_D = C_{D0} + k_1 C_L^2 + k_2 C_L \tag{7}$$

$$k_2 = -2k_1 C_{LminD} \tag{8}$$

$$C_{D0} = C_{Dmin} + k_1 C_{LminD}^2 \tag{9}$$

$$C_{LminD} = a(\alpha_{wing\_minD} - \alpha_{L=0} \tag{10}$$

$$C_{D_min} = C_{fe} \frac{s_{wet}}{s_{ref}} \tag{11}$$

$$L = \frac{1}{2}\rho V_\infty^2 S C_L \tag{12}$$

I. Discussion Question 1

When converting 2D infinite data to 3D finite data, induced drag must be added to the finite wing. The induced drag, also known as the drag due to lift, faces downstream and is caused by the action of the tip vertices. Additionally, the slope of the lift curve for a finite wing is less than that for an infinite wing.

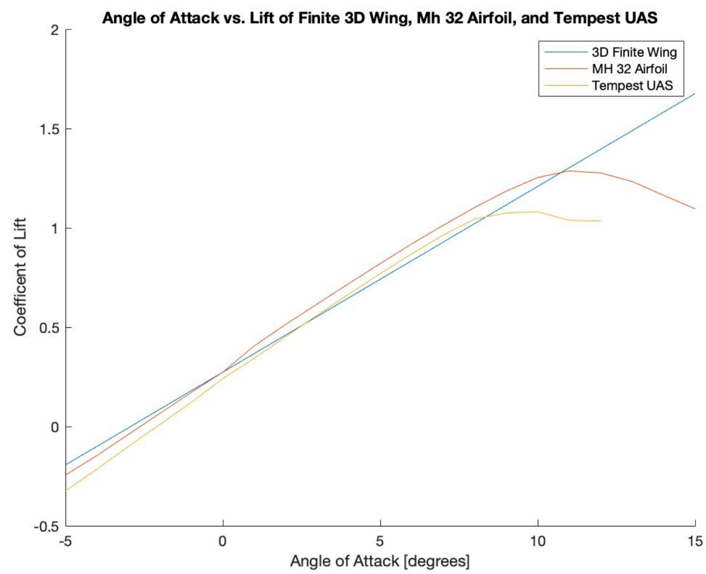

Fig. 1 Coefficient of Lift vs. Angle of Attack

As shown in the figure, the 3D finite data begins with a smaller slope in comparison to the 2D infinite data and this relationship remains constant throughout the data; therefore, the data in this figure is consistent with the fact that there is a reduction in the lift curve slope for a finite wing.

The angle of attack for zero lift should be the same for finite and infinite wings. Based on the data in the figure, the slopes do not converge until they reach a value for the coefficient of lift of around 0.30. The slight variance in the data is most likely due to possible inaccuracies and human error associated with data collection. Once a certain angle of attack is reached, stall begins to occur and there is significant reduction in the lift curve slope. Note the formulation for the 3D finite wing data only models the linear portion of the slope; as a result, the nonlinear portion of data for stall is only shown for the 2D data.

II. Discussion Question 2

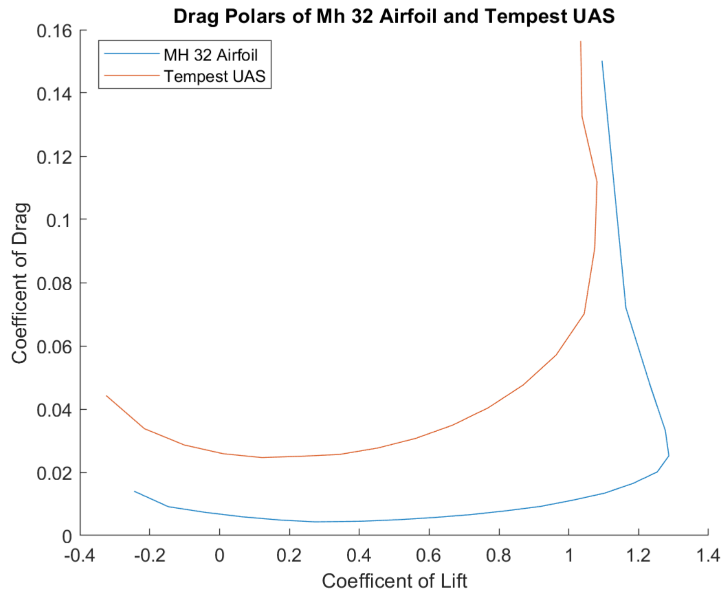

Fig. 2 Calculated vs Estimated Drag Polar

General trends of the drag polar for the theoretical model (MH 32 Airfoil) closely lines up with the provided CFD of the Tempest UAS as depicted in Figure 2; however, there is a consistent offset of about 0.4 which suggests a systematic error.

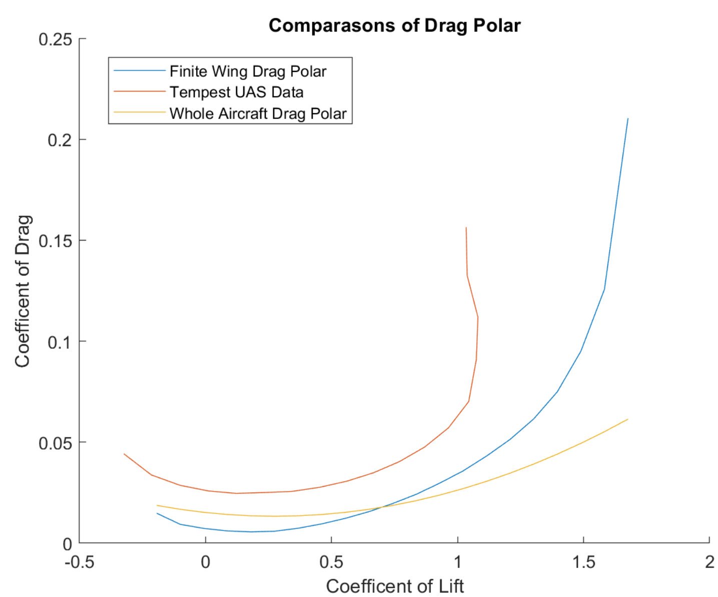

Fig. 3 Calculated Vs Estimated Drag Polar

In Figure 3, both the drag polars for the finite wing and the entire aircraft is less than the drag polar of the CFD. All three show a similar trend except for the whole aircraft drag polar which has a smaller slope as the coefficient of lift increases. As previously discussed, induced drag must be accounted for when dealing with the 3D finite wing data. Induced drag has a direct relationship with the square of the coefficient of lift. As the angle increases, the lift coefficient increases, and this changes the amount of induced drag.

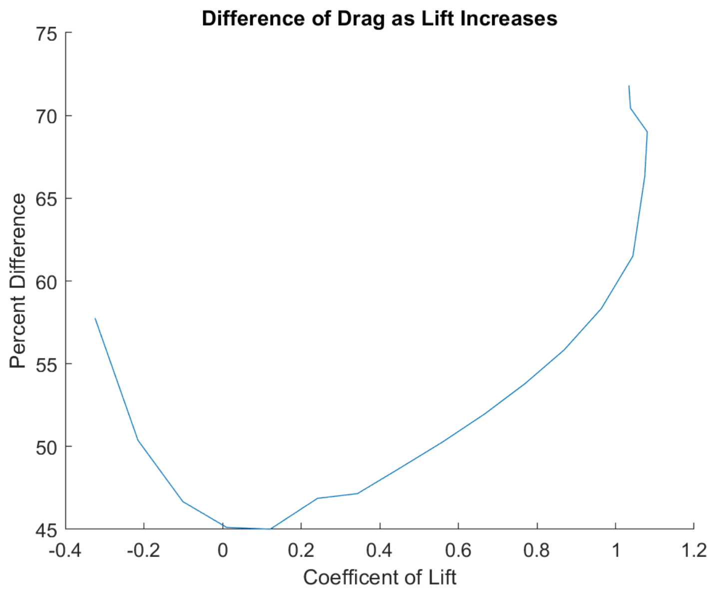

Fig. 4 Quantified Percent Difference of Drag Polars as CL Increases

Figure 4 illustrates the difference between the CFD drag polar and the calculated drag polar. The percent difference is minimized at an angle of attack of 1° of 45.01% and maximized at an angle of attack of -5° and 12°. The majority of the error in the calculated drag polar comes from parasite drag. Parasite drag includes the wetted area which may be a large source of the percent difference. Both drag due-to-lift and parasite drag terms depend on many of the same variables. Both contain C_L^2 terms which would contribute significant error. An improvement that can be made would be with the calculation of CL. A more accurate CL would yield a more accurate drag polar which can be achieved by having more/better data. Another improvement would be to eliminate systematic bias of the measurements made.

III. Discussion Question 3

As seen in Figure 5, the estimated lift to drag ratio (L/D) of the finite 3D wing is significantly larger than the actual L/D of the UAS Tempest CFD data. After quantifying a percent difference, the L/D of the estimated wing is on average 37.1% larger than the L/D of the UAS Tempest.

The Maximum L/D of the estimated finite 3D wing was calculated to be approximately 49.7 while the angle of attack at which this occurred was 1°. At the maximum L/D, the C_L of the finite 3D wing was found to be 0.3672. Using the C_L found at the max L/D of the finite wing, the velocity can be calculated using $V_\infty = \sqrt{\frac{2L}{C_L S\rho}}$ which results in a velocity of $V_\infty = 21.8$ m/s.

In comparison to the UAS Tempest, the maximum L/D is approximately 19.1 and the angle of attack at which this occurs is 4. The C_L of the UAS Tempest at its max L/D is 0.6663, and using the above equation to solve for the velocity, the UAS Tempest would fly at a velocity of $V_\infty = 16.2$ m/s. Although the C_L of the UAS Tempest at its max L/D is nearly double that of the estimated wing calculation, the C_D of the UAS Tempest at its maximum L/D is much larger at 0.0349 when compared to the C_D of the estimated wing at its maximum L/D which is 0.0074. This is likely the cause of the large percent variance between the L/D curves of the two data sets.

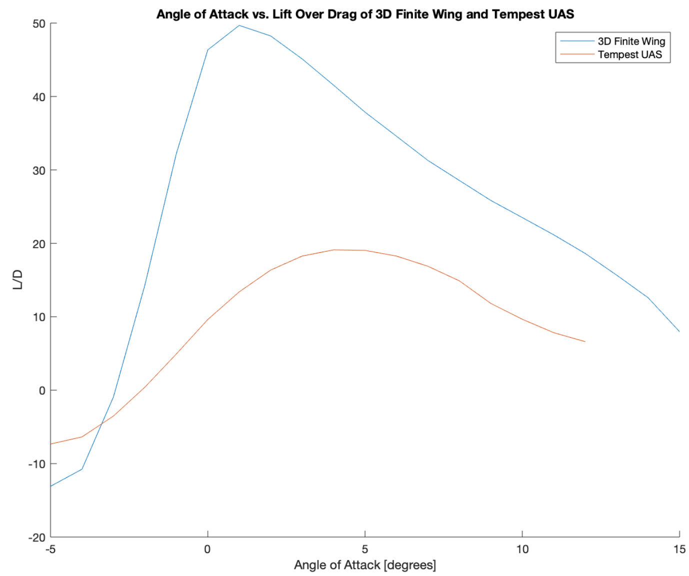

Fig. 5 L/D Comparison between estimated finite 3D wing and Tempest UAS

IV. Discussion Question 4

Glide flight conditions for maximum range can be found with Equation 1, as well as, the use of the estimated drag polar and lift plot. Additionally, the CFD derived drag polar and lift curve plot are used to achieve the value of maximum range where the ratio of lift to drag is maximized. In order to determine the angle of attack for the estimated maximum range, the slope of the lift curve graph for the finite wing is used. The optimal angle of attack is found when the coefficient of lift is equal to zero. Then using the found slope and intercept with the previously found values of angle of attack and C_L max, an angle of attack where velocity is maximized can be found. The C_L value used was calculated using the C_D from Equations 6 and 1. Maximum velocity was found using GTOW, Equation 14, and the calculated maximum C_L. Assuming steady, unaccelerated, power-off glide, and a small glide angle, the values that would be used to calculate maximum range are shown in Table 1 below.

Glide flight conditions for maximum endurance can be found with Equation 2, as well as, the estimated drag polar and lift plot. The CFD derived drag polar and lift curve plot are also used to achieve the value of maximize endurance where P_R is minimized. In order to solve for angle of attack and velocity, the same processes used for range are used with the substitution of Equation 2 for Equation 1. These calculations will result in a maximum velocity with a corresponding angle of attack. Assuming steady, unaccelerated, power-off glide, and a small glide angle, the values that would be used to calculate maximum endurance are shown in Table 1 below.

Angle of Attack Range - Estimated	2.69 °
Velocity Range - Estimated	14.91 m/s
Angle of Attack Endurance - Estimated	2.52 °
Velocity Endurance - Estimated	11.33 m/s

For the tempest, the value of C_{Lmax} was found at the maximum L/D of the Tempest found earlier in Section 3. Using C_{Lmax}, the air speed velocity can be found using a derivation of equation 12, $V_\infty = \sqrt{\frac{2GTOW}{\rho S C_{Lmax}}}$. Next, the angle of attack when lift is equal to zero, $\alpha_{L=0}$, was found using Equation 3. Using $\alpha_{L=0}$ the angle of attack, α_{max}, at which the Tempest flies at while flying at its V_∞ found earlier can be found using Equation 3 again. Similar to the range calculation for the Tempest, the endurance can be found using Equation 2 where a new C_{Lmax} can be found. After solving the new C_{Lmax}, repeat the process using Equation 12 and Equation 3 to find the V_∞ and α_{max} respectively.

Angle of Attack Range - Tempest	2.53 °
Velocity Range - Tempest	16.22 m/s
Angle of Attack Endurance - Tempest	10.95 °
Velocity Endurance - Tempest	11.13 m/s

The percent differences between calculated performance points for max range and endurance for estimated and Tempest are shown below.

Angle of Attack Range - % Difference	6.38 %
Velocity Range - % Difference	8.03 %
Angle of Attack Endurance - % Difference	77.03 %
Velocity Endurance - % Difference	1.80 %

Differences in performance flights conditions versus those derived from the plots can be accounted for by flat plate assumptions and/or the induced drag effects for a finite wing versus an entire body. There is significant difference in the angle of attack for endurance. This is due to the inclusion of induced drag and its effects on the angle of attack and therefore the coefficient of lift. The angle of attack for endurance has the most error due to this method's coefficient of lift calculation. In order to minimize this error, for maximum endurance, (minimum sink rate) one must operate at the minimum power required condition.

V. Discussion Question 5

To begin the improvements to this design, figures 1, 4, 5, and 6 need to be analyzed in order to understand which aspects need to be focused on. The curves shown in the Coefficient of Lift (C_L) versus Angle of Attack graph have small differences around the value for zero lift. The 3D wing has a sharper angle of attack, which points this vehicle towards the ground more. The Tempest UAS has a more level angle of attack when there isn't any lift, which doesn't allow for the nose of the plane to dip down too low before stalling; this would be part of the design improvements.

A main goal of this lab includes maximizing the L/D ratio in order to accomplish maximum range and the most efficient fuel consumption, and minimize the required thrust for the aircraft. This can be done by decreasing the coefficient of drag, thus drag overall, or increasing the coefficient of lift, which increases the amount of lift the aircraft can withstand. Since the coefficient of drag is dependent on the coefficient of lift squared, the affects of increasing this value needs to be considered as well. In order to combat the increase of the coefficient of drag with the increase of the coefficient of lift, the parasite drag value can be decreased. This is seen in figure 6 as the tempest UAS has a much larger parasite drag since its curve is shifted up. This decrease will shift the C_D versus angle of attack curve down, which will decrease the values overall.

The parasite drag can also be decreased by changing the material of the plane, which changes the skin friction. A second way to decrease this value is by lowering the pressure difference above and below the airfoil, which is accomplished by decreasing the airfoil height; this needs to be done very carefully so that the wings do not fold under pressure. As discussed in section 1, the parasite drag values do not match up at zero lift, so this will be a critical task in improving the overall design since this will provide more accurate data.

Induced drag can be decreased by changing the shape of the wing, which affects the aspect ratio and the Oswald's Efficiency. The taper ratio can be increased changing the shape of the chord so that it is not a straight line across the wings. The angle of attack where zero lift occurs can also be adjusted by twisting the wings. The goal would be to decrease the angle of attack where the lift is zero; this would give the aircraft leeway for negative angle of

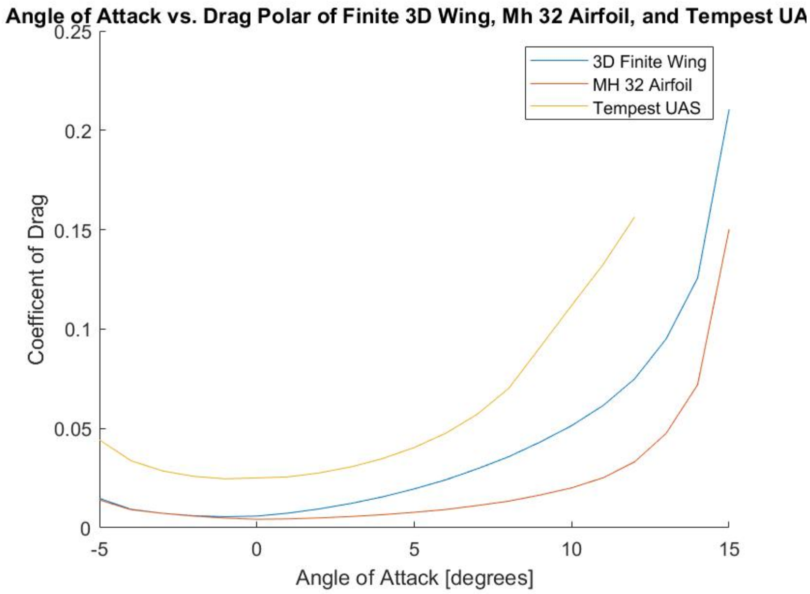

Fig. 6 Polar Drag Coefficient Compared to Angle of Attack for the finite 3D wing and the Tempest UAS

attacks, providing more lift for greater angles of attack. This is seen in the equation 3, which relates the C_L to the differences of actual angle of attack and the angle attack for zero lift; the greater this difference, the greater C_L will be, increasing the L/D ratio.

Lift can also be increased by increasing the plane form area. The considerations that play a role in these changes are the aspect ratio and the Oswald's Efficiency. The aspect ratio should decrease, reinforcing that the plane form area should be increased. The increase in the aspect ratio will decrease the induced drag term, which decreases the overall drag.

The Oswald's efficiency of a wing can be calculated using various methods. One such method was given; however, instead a different equation was used to calculate the efficiency as it was more accurate for the remained of the calculations. The calculation was done using the equation $e = \frac{1}{1.05+0.007\pi S}$.

Each of these various characteristics will be adjusted in order to find the ideal vehicle design that will maximize range and endurance.

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Appendix A

MATLAB Code

MATLAB Code

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Purpose: Convert 2D to 3D data for coefficient of lift and drag.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% House Keeping
clear all
close all
clc

%Defining Variables
a_Attack = -5:12; %Entire Plane
C_L = [-0.32438 -0.21503 -0.10081 0.010503 0.12155 0.24163 0.34336 0.45256 0.56037 0.66625 ...
    0.76942 0.86923 0.96386 1.0441 1.0743 1.0807 1.0379 1.034]; %Entire Plane
C_D = [0.044251 0.033783 0.028627 0.025864 0.024643 0.025099 0.025635 0.02766 0.030677 ...
    0.034855 0.040403 0.04759 0.057108 0.070132 0.090921 0.11193 0.13254 0.15645]; %Entire ...
    Plane
a_attack = [-5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15]; %Just Wings
C_l = [-0.2446 -0.1465 -0.0401 0.0658 0.1717 0.2737 0.4058 0.5143 0.6167 0.7194 0.8201 ...
    0.9193 1.0129 1.1027 1.1844 1.2533 1.2865 1.2763 1.2329 1.1635 1.0951]; %Just Wings
C_d = [0.0140 0.0091 0.0073 0.0059 0.0049 0.0043 0.0045 0.0050 0.0057 0.0066 0.0078 0.0092 ...
    0.0112 0.0134 0.0165 0.0201 0.0252 0.0332 0.0475 0.0720 0.1502]; %Just Wings

%Plotting angle of attack and coefficients for lift and drag
%3D Plots
figure(1);
hold on;
plot(a_Attack,C_L)
plot(a_Attack,C_D)
```

```
title('Angle of Attack vs. Lift and Drag Coefficients of Tempest UAS')
xlabel('Angle of Attack [degrees]')
ylabel('Coefficents for Lift and Drag')

%2D Plots
figure(2);
hold on;
plot(a_attack,C_l)
plot(a_attack,C_d)
title('Angle of Attack vs. Lift and Drag Coefficients of Airfoil')
xlabel('Angle of Attack [degrees]')
ylabel('Coefficents for Lift and Drag')

%Determining the slope of each curve

%Sparcing Data for 2D wing plot
a_0data = a_attack(1:14);
C_ldata = C_l(1:14);
C_ddata = C_d(1:14);

%Using y=mx+b to find a_0 on 2D wing plot
a_0 = polyfit(a_0data,C_ldata,1);
a_02D = a_0(1);

%Using Equation 3.1 to solve for a for the wing
e = 0.9387; %Given Value
AR= 16.5; %
a_wing3D = a_02D/(1+((57.3*a_02D)/(pi*e*AR)));

%Sparcing data for 2D wing plot
A_data = a_attack(1:12);
C_Ldata = C_L(1:12);
C_Ddata = C_D(1:12);

%Using y=mx+b to find a_0 on 2D airfoil plot
A = polyfit(A_data,C_Ldata,1);
a_0airfoil = A(1);

%Using Equation 3.1 to solve for a_0 on 2D airfoil plot
a_airfoil3D = a_0airfoil/(1+(57.3*a_0airfoil)/(pi*e*AR)); %3D slope

%Calculating the angle of attack when lift = 0
%Using y=mx+b to solve for a_attack3D for airfoil
%Lift = 1/2 *C_l*rho*V^2*S
a_attack3Dwing = -C_l(6)/a_wing3D;

%Coefficient of Lift for 3D finite wing
CL_wing3D = a_wing3D.*(a_attack-a_attack3Dwing);

%Coefficient of Drag for 3D finite wing
CD_wing3D = C_d+(CL_wing3D.^2/(pi*e*AR));

%% Question 1

figure(3);
hold on;
plot(a_attack,CL_wing3D)
% plot(a_attack,CD_wing3D)

% Overlaying the
plot(a_attack,C_l)
plot(a_Attack,C_L)

legend('3D Finite Wing', 'MH 32 Airfoil', 'Tempest UAS')
%title('Angle of Attack vs. Lift and Drag Coefficients of 3D Finite Wing')
title('Angle of Attack vs. Lift of Finite 3D Wing, Mh 32 Airfoil, and Tempest UAS')
xlabel('Angle of Attack [degrees]')
ylabel('Coefficent of Lift')
```

```

%% Question 3

L_D = CL_wing3D./CD_wing3D;
CL_CD = C_L./C_D;
% Plotting L/D vs aoa of wing and tempest data
figure(5);
hold on;
plot(a_attack, L_D)
title('Angle of Attack vs. Lift Over Drag of 3D Finite Wing and Tempest UAS')
xlabel('Angle of Attack [degrees]')
ylabel('L/D')
% Overlaying Tempest UAS Data for Question 3
plot(a_Attack, CL_CD)
legend('3D Finite Wing', 'Tempest UAS')
hold off

% Calculating percent difference between two curves
CL_Difference = (((CL_wing3D(1:18) - C_L) ./ C_L) * 100);
CL_Difference_Avg = mean(CL_Difference);
% Max percent difference is at 4 degrees which is 725% difference, avg of
% 37%

% Estimated Max L/D and V/AoA at Max L/D
for i = 1:length(L_D)
    if L_D(i) == max(L_D)
        Max_LD = max(L_D);
        Max_AoA = i - 6;
        % Max velocity found at end with assumption of flying at 1.8km height
    end
end

for i = 1:length(CL_CD)
    if CL_CD(i) == max(CL_CD)
        Max_LD_UAS = max(CL_CD);
        Max_AoA_UAS = i - 6;
        % Max velocity found at end with assumption of flying at 1.8km height
    end
end
%%
% Using equation 3.6 to solve for CD_min to eventually solve 3.4a/b for CD
C_fe = 0.004;
S_wet = 2.327;
S_ref = 0.698;
CD_min = (C_fe * S_wet) / (S_ref);

% Initial Estimation of Oswalds efficiency to solve for 3.4a/b
s = 0.995;
S = 0.698;
e_0 = 1 / (1.05 + 0.007*pi*S);

% Solving 3.3b for k1 to solve 3.4a/b
k1 = 1 / (pi*e_0*AR);

% Solving 3.5 for CL_minD for 3.4a/b eventually
CL_minD = a_wing3D*(CD_wing3D(5) - a_attack3Dwing);

% Solving 3.4a for CD of entire aircraft
CD_Aircraft = CD_min + k1*(CL_wing3D - CL_minD).^2;
CD_0 = CD_min + k1*CL_minD.^2;

%Calculating The coefficients of Drag
k2 = -2*k1*CL_minD;
CD = CD_0 + k1*CL_wing3D.^2 + k2*CL_wing3D;

%Plotting new drag polar
figure(6)
hold on
```

```
plot(a_attack,CD)
title('Drag Coefiificent for the Entire Aircraft')
xlabel('Angle of Attack [degrees]')
ylabel('Draf Coefficient')
hold off

% Now that we have CD_0 we can do max range and max endurance calculations
height = 1800; %[m]
GTOW = 6.4*9.81; %[kg]
rho = 1.026937; %[kg/m^3]
S = 0.698; %[m^2] @ 1.8 km

%determing angle of attack for zero lift for 3D airfoil
eq = polyfit(a_attack, CL_wing3D,1);
a_L0 = eq(1);
b = eq(2);

% Max Range Finite Wing
CL_max = sqrt(CD_0/k1);
V_max = sqrt(2*GTOW./(rho.*S.*CL_max)); %[m/s]
a_attackL0 = (CL_max - b)/a_L0;
a_attackVmax = (CL_max/a_airfoil3D) - a_attackL0;

% Max Endurance Finite Wing
CL_max_E = sqrt(3*CD_0/k1);
V_max_E = sqrt(2*GTOW./(rho.*S.*CL_max_E)); %[m/s]
a_attackL0_E = (CL_max_E - b)/a_L0;
a_attackVmax_E = (CL_max_E/a_airfoil3D) - a_attackL0_E;

%determing angle of attack for zero lift for 3D airfoil
eq = polyfit(a_Attack, C_L,1);
a_L0_UAS = eq(1);
b_UAS = eq(2);

% Max Range of Tempest
V_max_UAS = sqrt(2*GTOW./(rho.*S.*C_L(10))); %[m/s]
a_attackL0_UAS = (C_L(10) - b_UAS)/a_L0_UAS;
a_attackVmax_UAS = (C_L(10)/a_L0_UAS) - a_attackL0_UAS;

% Max Endurance of Tempest
C_D_E = k1*C_L(10);
C_L_E = sqrt((3*C_D_E)/k1);
V_max_UAS_E = sqrt(2*GTOW./(rho.*S.*C_L_E)); %[m/s]
a_attackL0_UAS_E = (C_L_E - b_UAS)/a_L0_UAS;
a_attackVmax_UAS_E = (C_L_E/a_L0_UAS) - a_attackL0_UAS;

% Percent Difference between 3D Finite Wing and Tempest
Finite_Tempest_Difference = 100*abs((V_max - V_max_UAS)/V_max_UAS)
Finite_Tempest_Difference_AoA = 100*abs((a_attackVmax - a_attackVmax_UAS)/a_attackVmax_UAS)
Finite_Tempest_Difference_E = 100*abs((V_max_E - V_max_UAS_E)/V_max_UAS_E)
Finite_Tempest_Difference_AoA_E = 100*abs((a_attackVmax_E - ...
    a_attackVmax_UAS_E)/a_attackVmax_UAS_E)

% V at Max L/D
V_LD = sqrt(2*GTOW./(rho.*S.*CL_wing3D(7)));
V_LD_UAS = sqrt(2*GTOW./(rho.*S.*C_L(10)));
%% Question 2
figure(7);
hold on;
%plot(a_attack,CD_wing3D)

% Overlaying the
plot(C_l,C_d)
plot(C_L,C_D)

legend('MH 32 Airfoil', 'Tempest UAS')
title('Drag Polars of Mh 32 Airfoil and Tempest UAS')
xlabel('Coefficent of Lift')
```

```
ylabel('Coefficent of Drag')

figure(8);
hold on;
plot(CL_wing3D,CD_wing3D)

% Overlaying the plots

plot(C_L,C_D)
plot(CL_wing3D,CD)


title('Comparasons of Drag Polar')
xlabel('Coefficent of Lift')
ylabel('Coefficent of Drag')
legend('Finite Wing Drag Polar', 'Tempest UAS Data','Whole Aircraft Drag Poalr')
hold off

figure(9);
hold on;

comp = CD(1:18);
differ = C_D - comp;
differ = (differ./C_D).*100;
plot(C_L,differ)


title('Difference of Drag as Lift Increases')
xlabel('Coefficent of Lift')
ylabel('Percent Difference')
```