University of Colorado - Boulder

ASEN 2004 - Vehicle Design and Performance

Aero Lab - Foundations of Aircraft Design

Milestone 1: Drag Polar Benchmarking

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Nomenclature

A	=	Aspect ratio
a_0	=	2-D airfoil lift curve slope
a	=	Finite wing lift curve slope
α	=	Angle of attack
$\alpha_{L=0}$	=	Angle of attack where lift is 0
C_d	=	2-D coefficient of drag
C_D	=	3-D coefficient of drag
C_l	=	2-D coefficient of lift
C_L	=	3-D coefficient of lift
e_0	=	Oswalds Efficiency Factor
ϕ_{LE}	=	Leading edge sweep angle

I. Tempest UAS Analysis

The first aircraft to be analyzed was the Tempest UAS, a small propeller-driven aircraft with an MH32 airfoil that was specifically designed for CU weather research. The graphical results of the analysis are shown in figure 1 below:

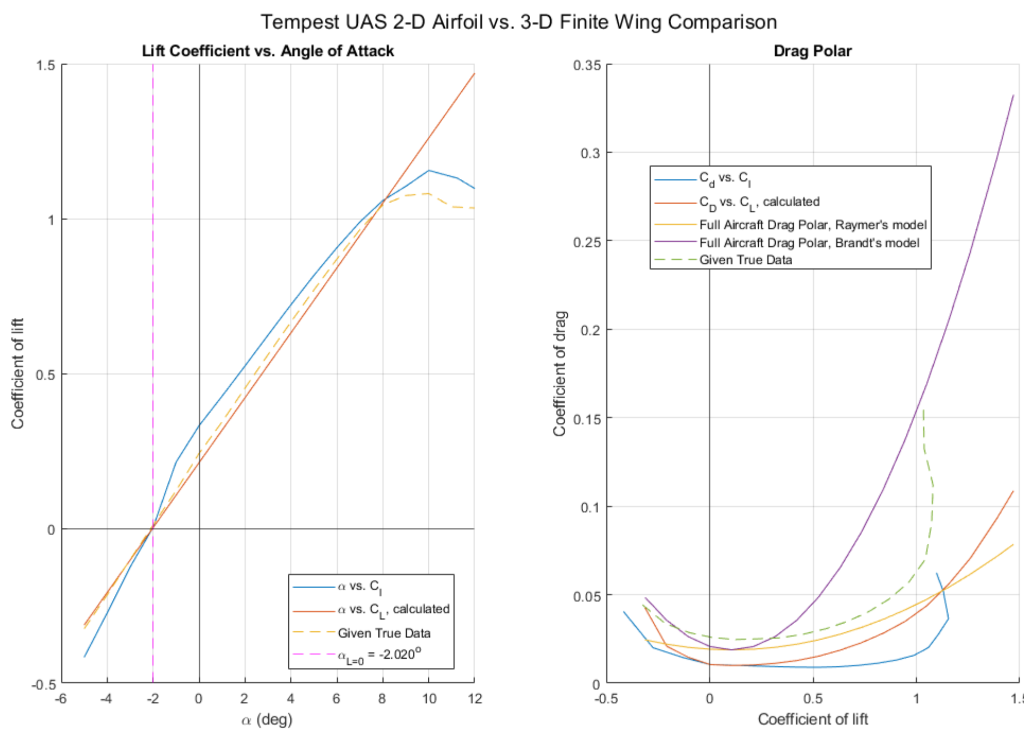


Fig. 1 Plots of 2-D airfoil data compared to a calculated 3-D finite wing approximation. The left plot shows the Tempest's lift curve, and the right plot shows the Tempest's drag polar for the 2-D airfoil, 3-D finite wing approximation, and two methods of approximating Oswalds Efficiency Factor. Both plots also include "true" 3-D data that was given alongside the 2-D information.

A. Tempest Lift Curve Comparison

The first characteristic that was analyzed when converting the 2-D airfoil data to a 3-D finite wing approximation was the relationship between coefficient of lift and angle of attack, or the lift curve. After converting, the finite wing approximation had a shallower lift curve slope than the 2-D airfoil, with values of $a = 0.1048$ and $a_0 = 0.1203$ respectively. This trend is shown in the left plot of figure 1, where the red line has a shallower slope than the linear section of the blue line. This makes sense, as the finite wing has to deal with the effects of downwash that reduces the amount of lift it can generate at any given angle of attack, whereas the 2-D airfoil doesn't have downwash at all. Thus, the 2-D airfoil will generate more apparent lift at each angle of attack, which corresponds with a steeper lift curve slope.

This finite wing approximation is only valid up until a bit before the 2-D stall angle, as the model used only gives the linear section of the lift curve. In order to model the 3-D stall section, either more advanced models would need to be used or the airfoil would need to be experimentally tested. In this case, experimental data came in the form of the "true" data. Before stall, however, the approximation holds up fairly well, with negligible variation between the red line and linear portion of the yellow line in figure 1.

B. Tempest Drag Polar Comparison

The second characteristic that was analyzed when converting the 2-D airfoil data to a 3-D finite wing approximation was the relationship between coefficient of lift and coefficient of drag, or the drag polar. In addition, the difference between the Tempest's wing drag polar and the drag polar for the entire aircraft was investigated.

1. 2-D airfoil vs. finite wing drag polar

After converting, the finite wing drag polar generally had a higher coefficient of drag for each coefficient of lift than the 2-D drag polar, which can be seen on the right plot of figure 1 as the red and blue lines respectively. This makes sense, once again due to downwash present on the finite wing that the 2-D airfoil doesn't have. Downwash creates induced drag that increases with lift, and this induced drag is added onto the pressure and skin friction drag already present for the 2-D airfoil. Thus, the presence of another drag component necessarily leads to the finite wing having higher drag coefficients overall.

This approximation is valid until the very extremes of the airfoil's possible coefficients of lift, where the vertical trend shown in the plot isn't relayed in the approximation. It is also valid only for modeling the wing's drag polar, as the fuselage and other parts of the airplane cause the true drag polar to be offset up and to the right of the wing polar. Thus, to get a better model of the aircraft's true drag polar, the other parts of the aircraft need to be taken into account

2. Wing vs. full aircraft drag polar

While the wing is the primary source of lift and a major contributor to drag, the rest of the aircraft cannot be ignored. After accounting for all the exposed area of the Tempest, the drag polar shifted up and to the right as compared to the wing drag polar, which can be seen in the right plot of figure 1 as the yellow and purple lines. This makes sense, as the fuselage of the Tempest contributes a little lift, shifting the polar right, and a decent amount of drag, shifting it up. Whereas the 2-D airfoil and finite wing approximations assume minimum drag at zero lift, the full aircraft polar reflects what happens in reality.

To model the full aircraft polar, two different methods of calculating Oswalds Efficiency Factor, e_0, were compared. The first method, from Raymer, was given with the assignment and can be seen as the yellow line in the right plot of figure 1. The equation for Raymer's method is as follows:

$$e_0 = 1.78(1 - 0.045A^{0.68}) - 0.64 \tag{1}$$

This method matched the curvature of the true data rather well, and would only require a small vertical adjustment to fully capture the true drag polar. The other method, from Brandt, was found in a reference given alongside the assignment, and can be seen as the purple line in the right plot of figure 1. The equation for Brandt's method is as follows:

$$e_0 = 4.31(1 - 0.045A^{0.68})cos(\phi_{LE})^{0.15} - 3.61 \tag{2}$$

Brandt's method is similar to Raymer's method, with the key difference being that it accounts for wing sweep. Since the Tempest doesn't have any wing sweep, the method doesn't capture the true data trends very well, and likely wouldn't with any additional translational offsets. However, Brandt's method will shine when it comes to analyzing the Boeing 747-200's drag polar, as the aircraft does have wing sweep.

II. Boeing 747-200 Analysis

The second aircraft to be analyzed was the Boeing 747-200, a large civilian transport with a BACJ airfoil that was designed to get passengers from location to location reliably. The graphical results of the analysis are shown in figure 2 below:

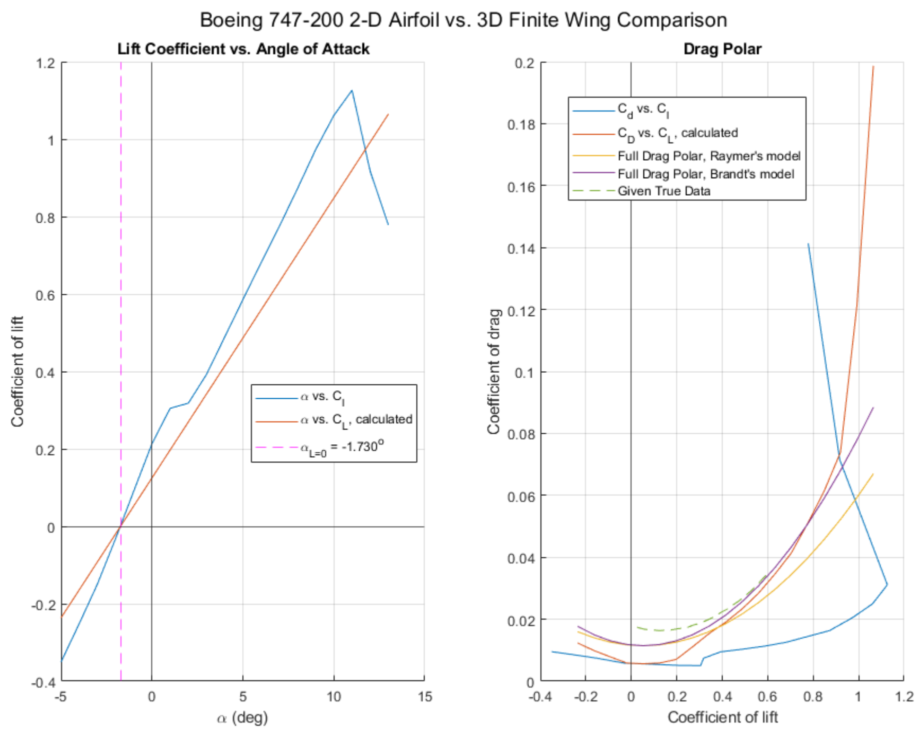


Fig. 2 Plots of 2-D airfoil data compared to a calculated 3-D finite wing approximation. The left plot shows the 747's lift curve, and the right plot shows the 747's drag polar for the 2-D airfoil, 3-D finite wing approximation, and two methods of approximating Oswalds Efficiency Factor. The right plot also includes "true" 3-D drag polar data that was given alongside the 2-D information.

Much of the reasoning for the 747's findings are almost identical to that of the Tempest's, and for the sake of brevity it is not repeated in this section unless necessary for clarity.

A. 747-200 Lift Curve Comparison

In analyzing the 747's lift curve, the same trends were found as for the Tempest, namely, a shallower lift curve slope for the finite wing approximation ($a = 0.0723$) than the 2-D airfoil ($a_0 = 0.0914$). Once again, this is due to the effects of downwash and its reduction of apparent lift.

Similar to the Tempest, this approximation is only valid up until just before the 2-D stall angle since the model used only gives the linear portion of the lift curve.

B. 747-200 Drag Polar Comparison

In addition to changes in its lift curve, changes in the 747's drag polar were also investigated.

1. 2-D airfoil vs. finite wing drag polar

While the original 2-D wing polar appears quite messy, the same trend was found for the 747 as the Tempest. Namely, that the finite wing drag polar generally had higher coefficients of drag for every coefficient of lift than the 2-D airfoil polar. This difference can be seen as the blue and red lines on the right plot of figure 2, and can be explained once again by the addition of an entirely separate component of drag: induced drag. However, unlike the Tempest, the 747's finite wing approximation seemed to deviate much faster from the 2-D data, which may be an indicator of the difference in size between the two aircraft.

Like the Tempest approximation, this approximation seems valid only until the extreme coefficients of lift for the 747, as the approximation isn't as vertical in those regions as the 2-D data would suggest. Another similarity is that this approximation only takes into account the wing, not the entire aircraft.

2. Wing vs. full aircraft drag polar

Similar to the Tempest, when accounting for the entire exposed area of the 747, the drag polar moved up and to the right from the 2-D data. This is for the same reasons as the Tempest, namely, that the body contributes a little lift and a large amount of drag.

Like the Tempest, two different methods were used to model the Oswalds Efficiency Factor of the 747: Raymer's model (equation 1) and Brandt's model (equation 2). Both methods come relatively close to the true data, with Brandt's method being slightly more accurate. The approximation based on Raymer's method can be seen as the yellow line in the right plot of figure 2, and the approximation based on Brandt's method can be seen as the purple line on the same plot.

Brandt's method works better on the 747 than it did on the Tempest for the simple fact that the 747 has a wing sweep angle, and the Tempest does not. Without that key piece of information, the model can't be applied to the Tempest with the same degree of accuracy as the 747.

III. Model Validity

While the approximate full aircraft drag polars of the Tempest and 747 are decent, they are by no means perfect nor 100% accurate. There are a few reasons for this, first and foremost being that major approximations were made in calculating the surface area of each aircraft. While the ideal way of obtaining these areas would be to pull the values from a CAD model, there wasn't one readily available and creating one from scratch would have taken more time than it was worth for these first order approximations. Thus, each aircraft was split into simpler, more easy to analyze geometrical shapes that didn't require a CAD model. This likely caused an underestimate in the wet area of each aircraft, which affected the drag polar by reducing each coefficient of drag slightly. Another reason these approximations don't exactly result in the given truth data is because they are first order approximations based on simple models. In order to get more accurate approximations, more advanced models would need to be used to advance these approximations from first order to second order and beyond. With all these approximations in mind, the offsets for all models from their respective true data are as follows:

- Tempest 3-D finite wing approximation: 30-40% of the true data
- Tempest Raymer approximation: 80-90% of the true data, up to $C_L = 1$
- Tempest Brandt approximation: 80-150% of the true data, up to $C_L = 1$
- Boeing 3-D finite wing approximation: 30-90% of the true data, up to $C_L = 0.6$
- Boeing Raymer approximation: 80% of the true data, up to $C_L = 0.6$
- Boeing Brandt approximation: 80-99% of the true data, up to $C_L = 0.6$

In terms of which model should be used to design the small glider in milestone 2, it depends on whether the glider is designed with swept wings or not. Raymer's method worked quite well with and without wing sweep, while Brandt's method excelled with swept wings but underperformed without them. Thus, if the glider has wing sweep it would be best to use the finite wing approximation with Brandt's method, and if the glider doesn't have wing sweep it would be best to use the finite wing approximation with Raymer's method.

Before starting the glider design, it would be worthwhile to investigate another method for approximating Oswalds Efficiency Factor that focuses on other aircraft characteristics, such as dihedral. Raymer's and Brandt's methods are almost identical, and it would be interesting to see the results of another method that is completely different from both.

IV. Collaboration

The only collaboration of note I had with this milestone was discussing ways of extracting data from multiple Excel sheets with Justin Travis, as well as comparing general plot trends to make sure we were both on the right track. I also assisted Justin McGregor get his minimum function implemented into his script, and I helped Joshua Camp debug his script.

Table of Contents

ASEN 2004 Lab 1 Milestone 1

```
By: Ian Faber
Started: 1/17/2022, 12:11 PM
Finished:

% Housekeeping
clc; clear; close all;

% Common constants
e = 0.9; % Wing span efficiency

% Extract names and number of Excel sheets
[sheetStatus, sheetNames] = xlsfinfo('Tempest UAS & B747 Airfoil and
 CFD Data for ASEN 2004 Aero Lab (Spr22).xlsx');
numSheets = length(sheetNames);

% Extract data
for k = 1:numSheets
    sheetData{k} = xlsread('Tempest UAS & B747 Airfoil and CFD Data
 for ASEN 2004 Aero Lab (Spr22).xlsx', sheetNames{k});
end

% Tempest UAS
Tempest2D = cell2mat(sheetData(1,2));
TempestTrue = cell2mat(sheetData(1,3));

% Boeing 747-200
Boeing2D = cell2mat(sheetData(1,5));
BoeingTrue = cell2mat(sheetData(1,6));
```

Tempest UAS Analysis and Plotting

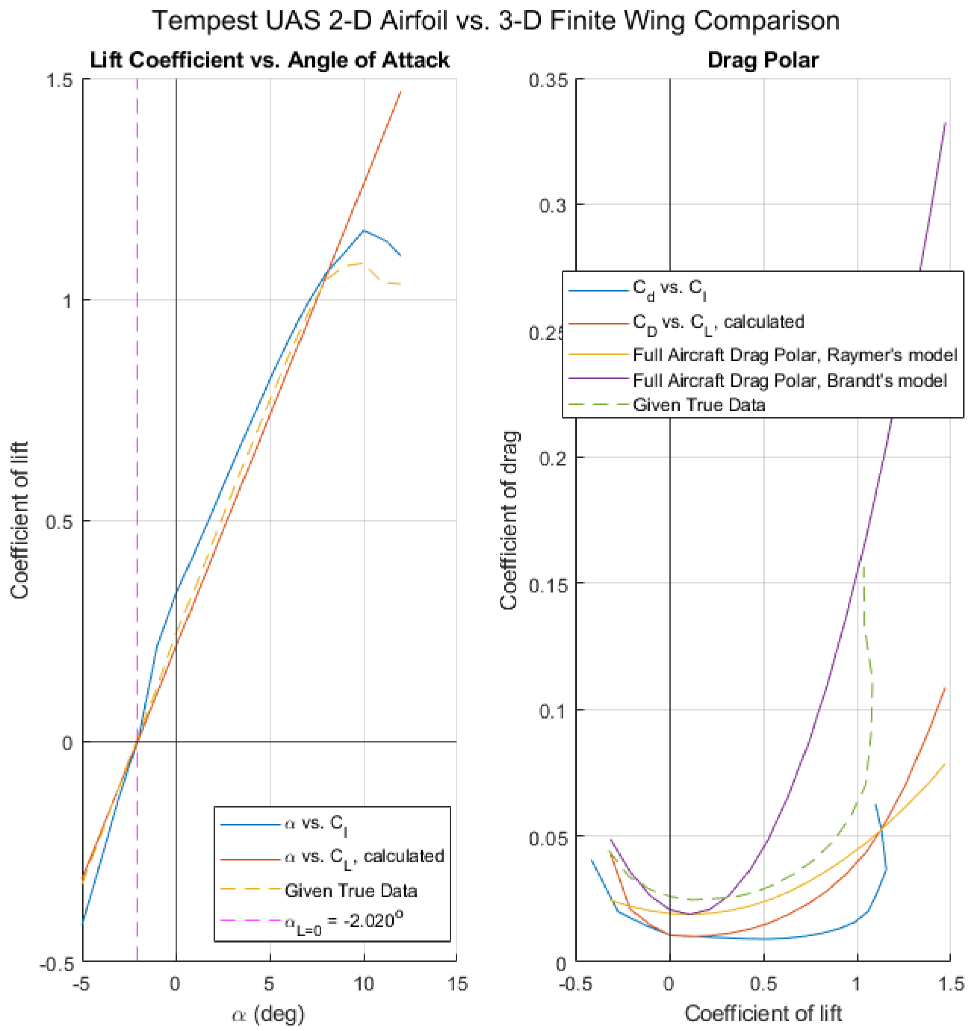
```
% Tempest Constants
SWetTempest = 2.285; % Approximation, m^2
SRefTempest = 0.667; % Approximation, m^2
CfeTempest = 0.0055; % Light, single prop aircraft
ARTempest = 16.5;
LESweepAngleTempest = 0; % Leading edge sweep angle for Brandt's
 method

% Analysis
```

```
% 2D airfoil
Tempest2DAlphas = Tempest2D(:,1);
TempestCl = Tempest2D(:,2);
TempestCd = Tempest2D(:,3);
TempestRe = Tempest2D(1,5);

% True data
TempestTrueAlphas = TempestTrue(:,1);
TempestTrueCL = TempestTrue(:,2);
TempestTrueCD = TempestTrue(:,3);

% Find a0
start = find(Tempest2DAlphas == -5);
stop = find(Tempest2DAlphas == 6);
[coef, ~] =
 leastSquares(Tempest2DAlphas(start:stop),TempestCl(start:stop),1);
a0 = coef(1)

% Find a
a = a0/(1+((57.3*a0)/(pi*e*ARTempest)))

% Find Alpha where L=0
[~, approxCurve] =
 leastSquares(Tempest2DAlphas(1:stop-7),TempestCl(1:stop-7),5);
alphaL0 = fzero(approxCurve, -2)

% Calculate CL from Cl
TempestCL = a*(Tempest2DAlphas - alphaL0);

% Calculate CD from Cd and CL
TempestCD = TempestCd + ((TempestCL.^2)/(pi*e*ARTempest));

% Calculate full drag polar with Raymer's Oswald factor model
e0 = 1.78*(1-0.045*(ARTempest)^0.68)-0.64;
k1 = 1/(pi*e0*ARTempest);

CDmin = CfeTempest*(SWetTempest/SRefTempest);

[~, index] = min(TempestCD);

CLminD = TempestCL(index)
k2 = -2*k1*CLminD;

CDo = CDmin + k1*(CLminD)^2;

TempestFullCDRaymer = CDo + k1*TempestCL.^2 + k2*TempestCL;

% Calculate full drag polar with Brandt's Oswald factor model
e0 = 4.61*(1-0.045*(ARTempest)^0.68)*cos(LESweepAngleTempest)^0.15 -
 3.1;
k1 = 1/(pi*e0*ARTempest);

CDmin = CfeTempest*(SWetTempest/SRefTempest);
```

```
[~, index] = min(TempestCD);
CLminD = TempestCL(index)
k2 = -2*k1*CLminD;

CDo = CDmin + k1*(CLminD)^2;

TempestFullCDBrandt = CDo + k1*TempestCL.^2 + k2*TempestCL;

%--------------------------------------------------------------------------
%
% Plotting
T = figure();
T.Position = [100 100 740 740];

sgtitle("Tempest UAS 2-D Airfoil vs. 3-D Finite Wing Comparison")

% Cl/CL vs. alpha
subplot(1,2,1)
hold on;
grid on;

TempestAlphaCl2D = plot(Tempest2DAlphas, TempestCl);
TempestAlphaCL = plot(Tempest2DAlphas, TempestCL);
TempestAlphaCLTrue = plot(TempestTrueAlphas, TempestTrueCL, '--');

% Utility lines
%alphaTest = -5:0.001:0;
%plot(alphaTest, approxCurve(alphaTest));
%plot(Tempest2DAlphas, a0Curve(Tempest2DAlphas));
alpha0Line = xline(alphaL0,'m--');
alpha0Label = sprintf("\\alpha_{L=0} = %.3f^o", alphaL0);
xline(0);
yline(0);

% Title, legend, labels
subset = [TempestAlphaCl2D, TempestAlphaCL, TempestAlphaCLTrue,
 alpha0Line];
titles = ["\alpha vs. C_l", "\alpha vs. C_L, calculated", "Given True
 Data", alpha0Label];

title('Lift Coefficient vs. Angle of Attack')
xlabel('\alpha (deg)')
ylabel('Coefficient of lift')
legend(subset, titles, 'Location', 'best');
hold off;

% Drag polar
subplot(1,2,2)
grid on;
hold on;

TempestDragPolar2D = plot(TempestCl, TempestCd);
TempestDragPolar3D = plot(TempestCL, TempestCD);
TempestRaymerFullDragPolar = plot(TempestCL, TempestFullCDRaymer);
```

```
TempestBrandtFullDragPolar = plot(TempestCL, TempestFullCDBrandt);
TempestDragPolarTrue = plot(TempestTrueCL, TempestTrueCD, '--');

% Utility lines
xline(0);
yline(0);

% Title, legend, labels
subset = [TempestDragPolar2D, TempestDragPolar3D,
 TempestRaymerFullDragPolar, TempestBrandtFullDragPolar,
 TempestDragPolarTrue];
titles = ["C_d vs. C_l", "C_D vs. C_L, calculated", "Full Aircraft
 Drag Polar, Raymer's model", "Full Aircraft Drag Polar, Brandt's
 model", "Given True Data"];

title('Drag Polar')
xlabel('Coefficient of lift')
ylabel('Coefficient of drag')
legend(subset, titles, 'Location', 'best')

hold off;
```

```
a0 =

    0.1203


a =

    0.1048


alphaL0 =

   -2.0203


CLminD =

    0.1070


CLminD =

    0.1070
```



Boeing 747-200 Analysis and Plotting

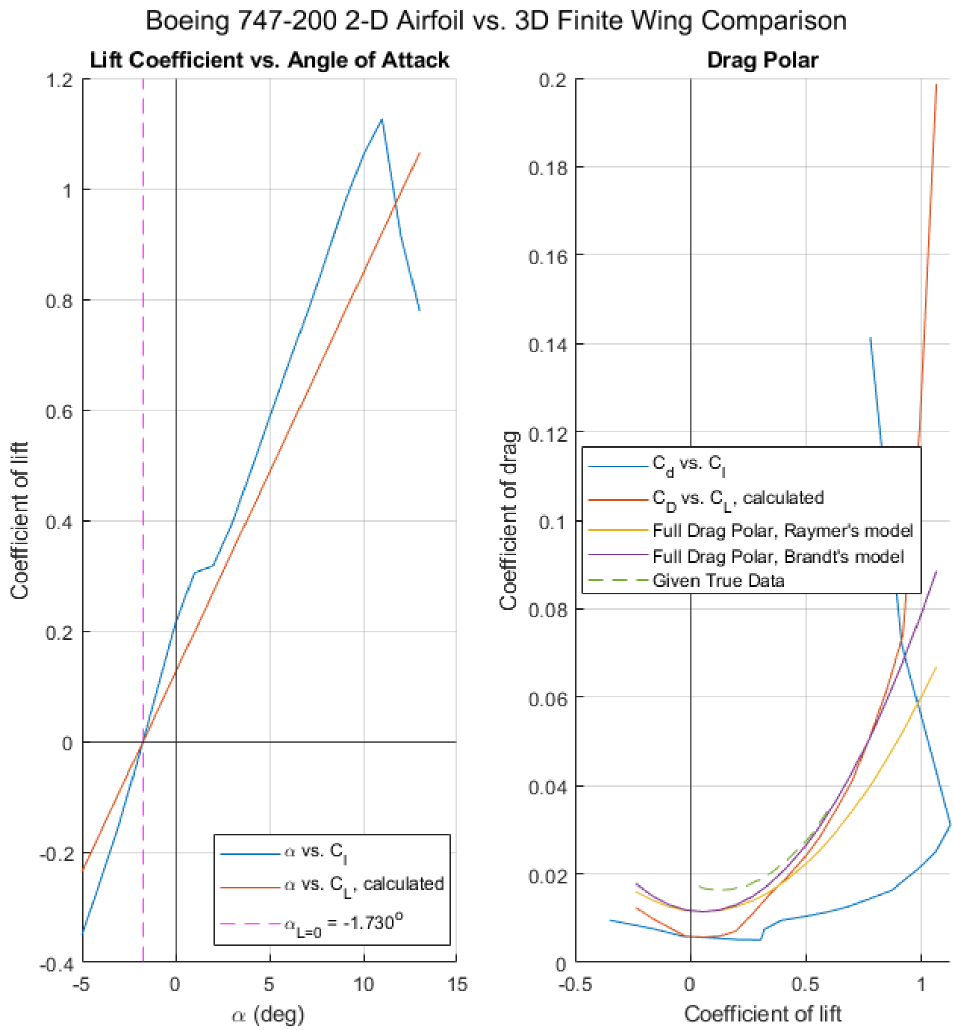
```
% Boeing Constants
SWetBoeing = 2175.93; % Approximation, m^2
SRefBoeing = 569.52; % Approximation, m^2
CfeBoeing = 0.003; % Civil transport
ARBoeing = 7;
% Leading edge sweep angle for Brandt's method, Boeing wing angle runs
% horizontally 75 feet, then vertically 100 feet, leading edge sweep
 angle
% is characterized by horizontal/vertical
LESweepAngleBoeing = atan2(75, 100);

% Analysis

% 2D airfoil
Boeing2DAlphas = Boeing2D(:,1);
```

```
BoeingCl = Boeing2D(:,2);
BoeingCd = Boeing2D(:,3);
BoeingRe = Boeing2D(1,5);

% True data
BoeingTrueCL = BoeingTrue(:,1);
BoeingTrueCD = BoeingTrue(:,2);

% Find a0
start = find(Boeing2DAlphas == -5);
stop = find(Boeing2DAlphas == 9);
[coef, ~] =
 leastSquares(Boeing2DAlphas(start:stop),BoeingCl(start:stop),1);
a0 = coef(1)

% Find a
a = a0/(1+((57.3*a0)/(pi*e*ARBoeing)))

% Find Alpha where L=0
[~, approxCurve] =
 leastSquares(Boeing2DAlphas(1:stop-7),BoeingCl(1:stop-7),5);
alphaL0 = fzero(approxCurve, -2)

% Calculate CL from Cl
BoeingCL = a*(Boeing2DAlphas - alphaL0);

% Calculate CD from Cd and CL
BoeingCD = BoeingCd + ((BoeingCL.^2)/(pi*e*ARBoeing));

% Calculate full drag polar with Raymer's Oswald factor model
e0 = 1.78*(1-0.045*(ARBoeing)^0.68)-0.64;
k1 = 1/(pi*e0*ARBoeing);

CDmin = CfeBoeing*(SWetBoeing/SRefBoeing);

[~, index] = min(BoeingCD);
CLminD = BoeingCL(index)
k2 = -2*k1*CLminD;

CDo = CDmin + k1*(CLminD)^2;

BoeingFullCD = CDo + k1*BoeingCL.^2 + k2*BoeingCL;

% Calculate full drag polar with Brandt's Oswald factor model
e0 = 4.61*(1-0.045*(ARBoeing)^0.68)*cos(LESweepAngleBoeing)^0.15 -
 3.1;
k1 = 1/(pi*e0*ARBoeing);

CDmin = CfeBoeing*(SWetBoeing/SRefBoeing);

[~, index] = min(BoeingCD);
CLminD = BoeingCL(index)
k2 = -2*k1*CLminD;
```

```
CDo = CDmin + k1*(CLminD)^2;

BoeingFullCDBrandt = CDo + k1*BoeingCL.^2 + k2*BoeingCL;

%-------------------------------------------------------------------------
%
% Plotting
B = figure();
B.Position = [940 100 740 740];

sgtitle("Boeing 747-200 2-D Airfoil vs. 3D Finite Wing Comparison")

% Cl/CL vs. alpha
subplot(1,2,1)
hold on;
grid on;

BoeingAlphaCl2D = plot(Boeing2DAlphas, BoeingCl);
BoeingAlphaCL = plot(Boeing2DAlphas, BoeingCL);

% Utility lines
%alphaTest = -5:0.001:0;
%plot(alphaTest, approxCurve(alphaTest));
%plot(Tempest2DAlphas, a0Curve(Tempest2DAlphas));
alpha0Line = xline(alphaL0,'m--');
alpha0Label = sprintf("\\alpha_{L=0} = %.3f^o", alphaL0);
xline(0);
yline(0);

% Title, legend, labels
subset = [BoeingAlphaCl2D, BoeingAlphaCL, alpha0Line];
titles = ["\alpha vs. C_l", "\alpha vs. C_L, calculated",
 alpha0Label];

title('Lift Coefficient vs. Angle of Attack')
xlabel('\alpha (deg)')
ylabel('Coefficient of lift')
legend(subset, titles, 'Location', 'best');
hold off;

% Drag polar
subplot(1,2,2)
grid on;
hold on;

BoeingDragPolar2D = plot(BoeingCl, BoeingCd);
BoeingDragPolar3D = plot(BoeingCL, BoeingCD);
BoeingRaymerFullDragPolar = plot(BoeingCL, BoeingFullCD);
BoeingBrandtFullDragPolar = plot(BoeingCL, BoeingFullCDBrandt);
BoeingDragPolarTrue = plot(BoeingTrueCL, BoeingTrueCD, '--');

% Utility lines
xline(0);
yline(0);
```

```
% Title, legend, labels
subset = [BoeingDragPolar2D, BoeingDragPolar3D,
 BoeingRaymerFullDragPolar, BoeingBrandtFullDragPolar,
 BoeingDragPolarTrue];
titles = ["C_d vs. C_l", "C_D vs. C_L, calculated", "Full Drag Polar,
 Raymer's model", "Full Drag Polar, Brandt's model", "Given True
 Data"];

title('Drag Polar')
xlabel('Coefficient of lift')
ylabel('Coefficient of drag')
legend(subset, titles, 'Location', 'best')

hold off;

%---------------------------------------------------------------------------
%

% Function from ASEN 2012

function [X,f] = leastSquares(t,y,p)
    % for writing this function, some skeleton code has been provided
 to
    % help you design the function to serve your purposes
    A = [];
    % write an expression for A, the input matrix
    for ii = 0:p
        col = t.^ii;
        A = [col, A];
    end
    % compute coefficient vector, x_hat
    x_hat = A\y;
    X = x_hat;

    % do not change the following lines of code. This will generate
 the
    % anonymous function handle "f" for you
%     f = '@(x)';
%     for i = 0:p
%         f = strcat(f,'+',strcat(string(x_hat(i+1)),'.*x.^',string(p-
i)));
%     end
%     eval(strcat('f = ',f,';'))

    while length(x_hat) < 7
        x_hat = [0;x_hat];
    end
    % workaround for MATLAB grader
    f = @(x) x_hat(1)*x.^6 + x_hat(2)*x.^5 + x_hat(3)*x.^4 +
 x_hat(4)*x.^3 + x_hat(5)*x.^2 + x_hat(6)*x + x_hat(7);

end
```

```
a0 =

    0.0914

a =

    0.0723

alphaL0 =

   -1.7297

CLminD =

    0.0527

CLminD =

    0.0527
```

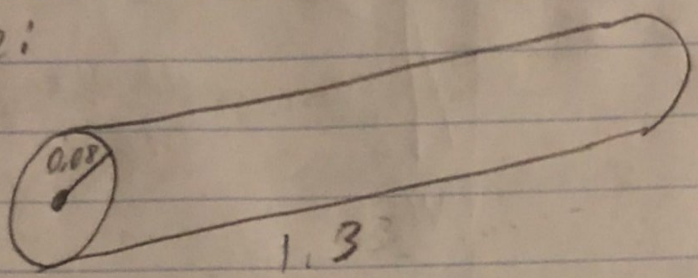


Published with MATLAB® R2021a

Tempest S_{wet}

$S_{wet} = 2 \cdot S_{wing} + S_{plane}$

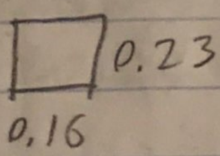
S_{plane}:



fuselage

+

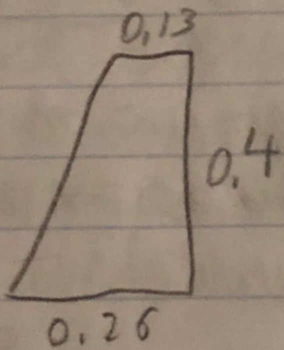
$S_{inside} \longrightarrow$



wing inside fuselage

+

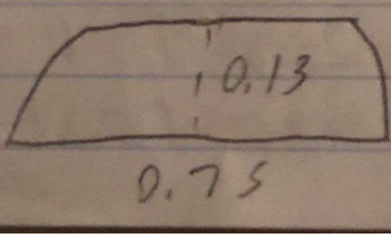
$2 \cdot$



vert. stabilizer

+

$2 \cdot$



Horiz. Stabilizer

$S_{ref} = S_{wing} + S_{inside}$

$S_{fuselage} = \pi(0,08)^2 + 2\pi(0.08)(1,3) = 0,674\ m^2$

$S_{inside} = 0,16 \cdot 0,23 = 0,0368\ m^2$

$S_{vert} = \frac{1}{2}(0,13+0,26)(0.4) = 0,078\ m^2$

$S_{horiz.} = 0,75(0,13) = 0,0975\ m^2$

$S_{ref} = 0,63 + 0,0368 = \underline{0,667\ m^2}$

$S_{plane} = S_{fuselage} + 2 \cdot S_{vert} + 2 \cdot S_{horiz.}$

$= 0,674 + 2(0,078) + 2(0.0975)$

$= 1,025\ m^2$

$S_{wet} = 2(0,63) + 1,025 = \underline{2,285\ m^2}$

$C_{Dmin} = C_{fe} \frac{S_{wet}}{S_{ref}} = 0.0055\left(\frac{2,285}{0,667}\right)$

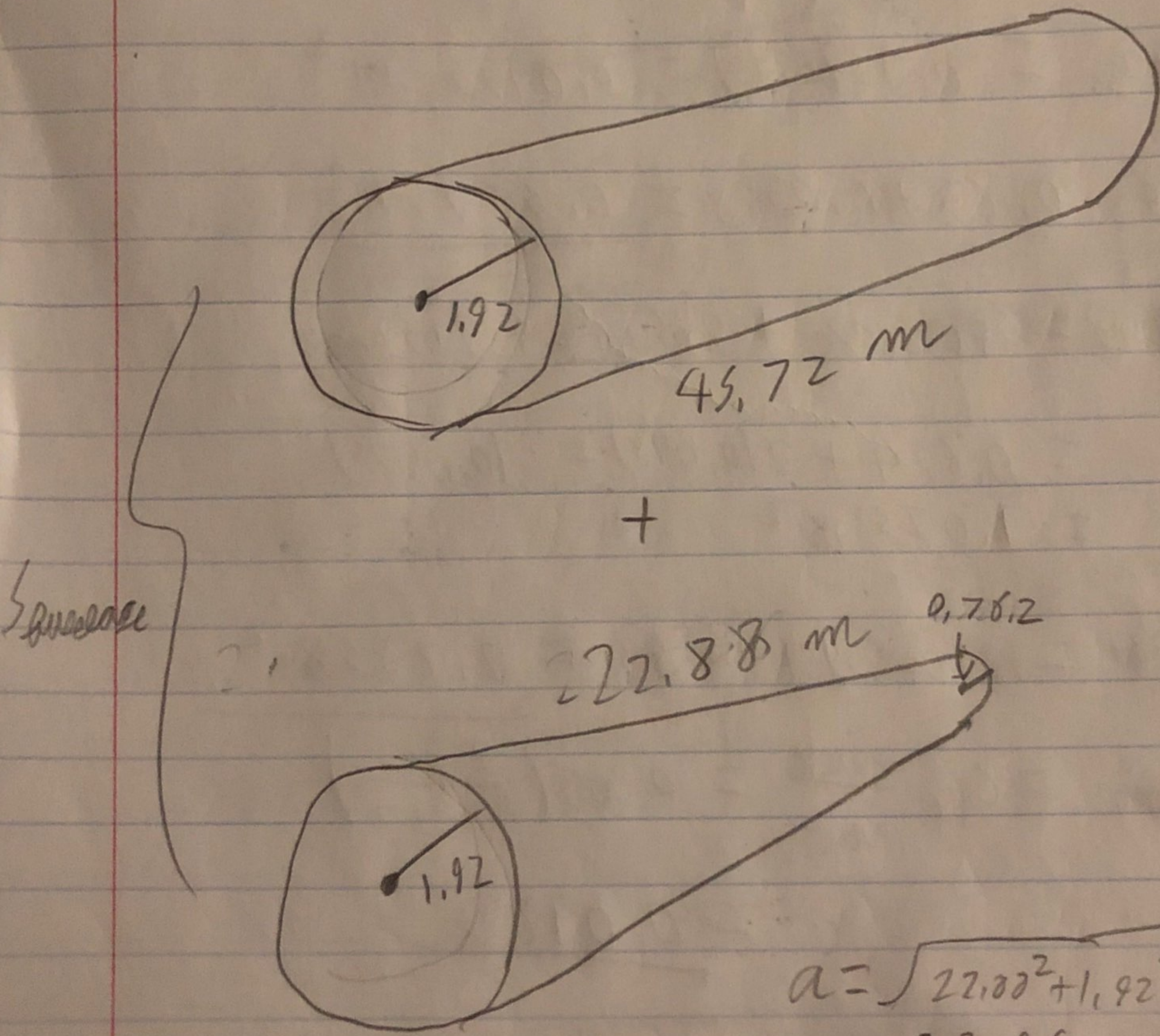
$= \underline{0,0188}$

Boeing S_{wet}

$S_{wet} = 2 \cdot S_{wing} + S_{plane}$

$S_{ref} = S_{wing} + S_{inside}$

S_{plane}:

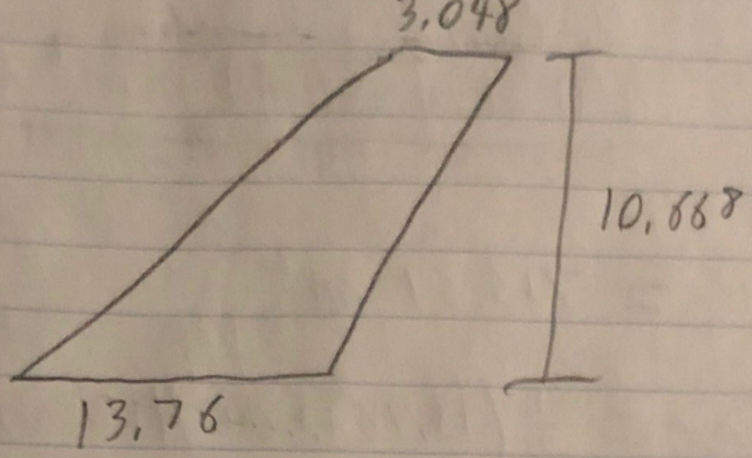


$a = \sqrt{22.88^2 + 1.92^2}$

$= 22.96\ m$

+

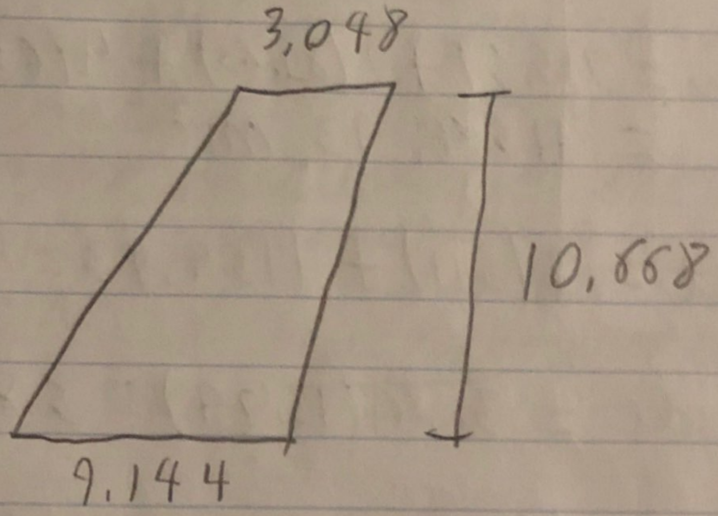
2.



S vert.

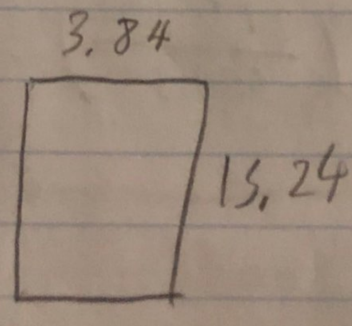
+

4.



S horiz.

S inside:



$$S_{fuselage} = \pi(1{,}92)^2 + 2\pi(1{,}92)(45{,}72) + \pi(1{,}92)^2 + \pi(0{,}762)^2 + \pi(1{,}92) \cdot \frac{\sqrt{\left(1{,}92 + \sqrt{22{,}96^2 - 22{,}88^2}\right)^2 + 22{,}88^2} + \sqrt{\left(1{,}92 - \sqrt{22{,}96^2 - 22{,}88^2}\right)^2 + 22{,}88^2}}{2}$$

$$= 715{,}51 \text{ m}^2$$

$$S_{vert} = \frac{1}{2}(13{,}76 + 3{,}048)(10{,}668) = 89{,}65 \text{ m}^2$$

$$S_{horiz.} = \frac{1}{2}(9{,}144 + 3{,}048)(10{,}668) = 65{,}03 \text{ m}^2$$

$$S_{plane} = 715{,}51 + 2(89{,}65) + 4(65{,}03)$$
$$= 1154{,}93 \text{ m}^2$$

$$S_{wet} = 2(511) + 1154{,}93 = \underline{2176{,}93 \text{ m}^2}$$

$$S_{inside} = 3{,}84(15{,}24) = 58{,}52 \text{ m}^2$$

$$S_{ref} = 511 + 58{,}52 = \underline{569{,}52 \text{ m}^2}$$

$$C_{Dmin} = 0{,}003\left(\frac{2176{,}93}{569{,}52}\right) = \underline{0{,}0115}$$

Scanned with CamScanner