AAE 334: Aerodynamics

HW4: XFLR5 Analysis

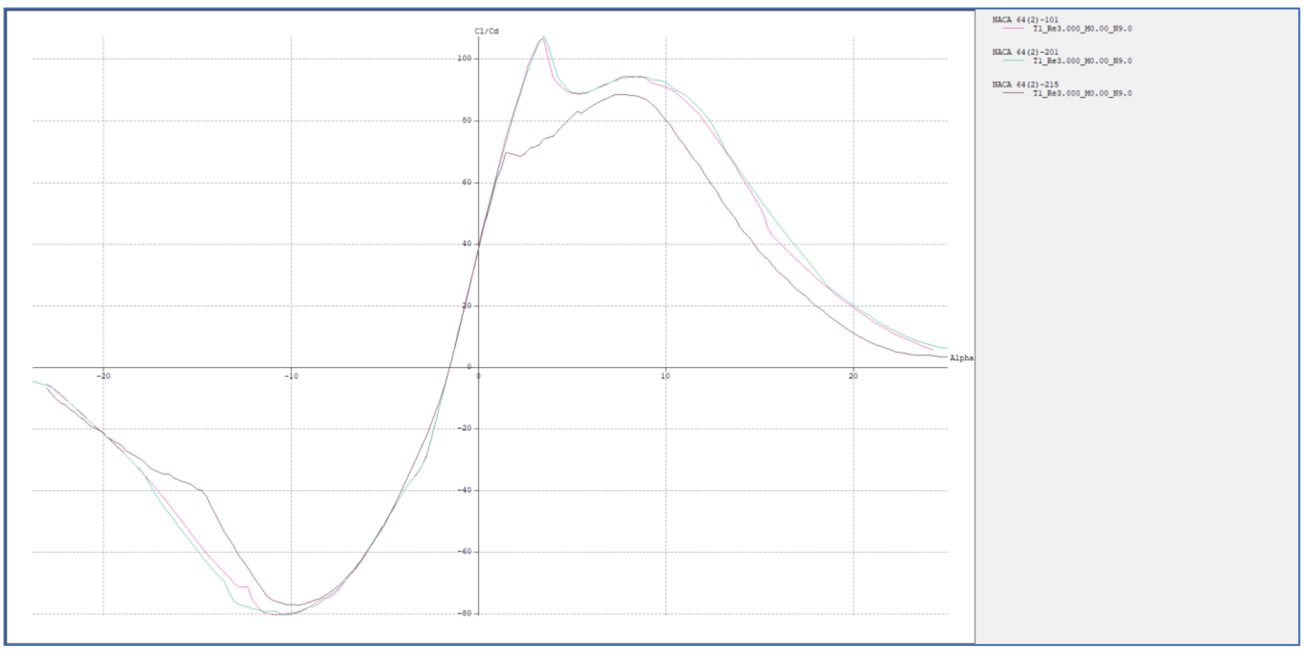
Dr. Blaisdell

Tomoki Koike

Friday February 15, 2020

[65 pts.] 1. Download the file `naca642215.dat` from the `HW4` folder on Blackboard. This is the geometry file for the NACA 64(2)-215 airfoil. The file has 51 points to define the geometry of the airfoil. Use XFLR5 to do the following:

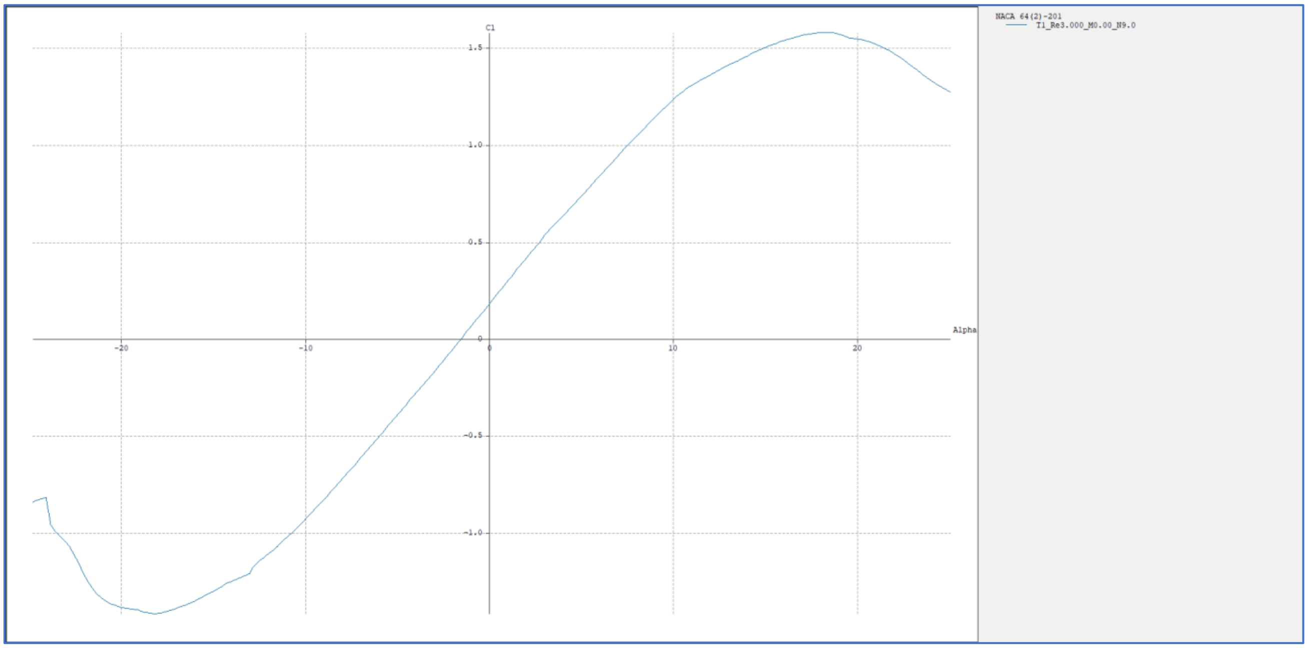
(a) [15 pts.] Run XFLR5 and open the airfoil coordinate data file. Then run an analysis at $Re = 3 \times 10^6$ and $Mach = 0.000$ (i.e., incompressible) for $\alpha = -25^\circ$ to $\alpha = 25^\circ$ with an increment of $\Delta\alpha = 0.25$ degrees. After running the code with 51 panels, use <**Design**> <**Refine Globally**> to increase the number of panels to 101. You will need to rename the airfoil; change its name to `naca642215-101`. Rerun the analysis with 101 panels. Then run the program again with 201 panels. XFLR5 will keep track of all three sets of results and plot them as different colored curves in the polar graphs. Consider the lift to drag ratio shown in the C_ℓ/C_d plot. You can plot this figure by itself by clicking on <**Graphs**><Graph 5>. Is the baseline geometry with 51 panels sufficient for determining the maximum lift to drag ratio and the angle of attack where that occurs? Are 101 panels sufficient? For the rest of the analysis below use the results with 201 panels. (You may have to close and restart XFLR5 and redo the analysis so that you only have results with 201 panels for the tasks outlined below.)



a-1) The baseline geometry with 51 panels is not sufficient because from the plot above we can see that for small angle of attacks the 51 panels condition largely deviates from the ones where we have 101 and 201 panels. At these small angles, the 101 and 201 panel baselines reach their maximum Cl/Cd ratio.

a-2) Comparing the 101 and 201 panel conditions we can observe a small level of deviation between them but they are overall following the same path, and therefore, we can say that 101 panels yield a compromisable result. However, to assure the best quality of analysis using 201 panels would be better.

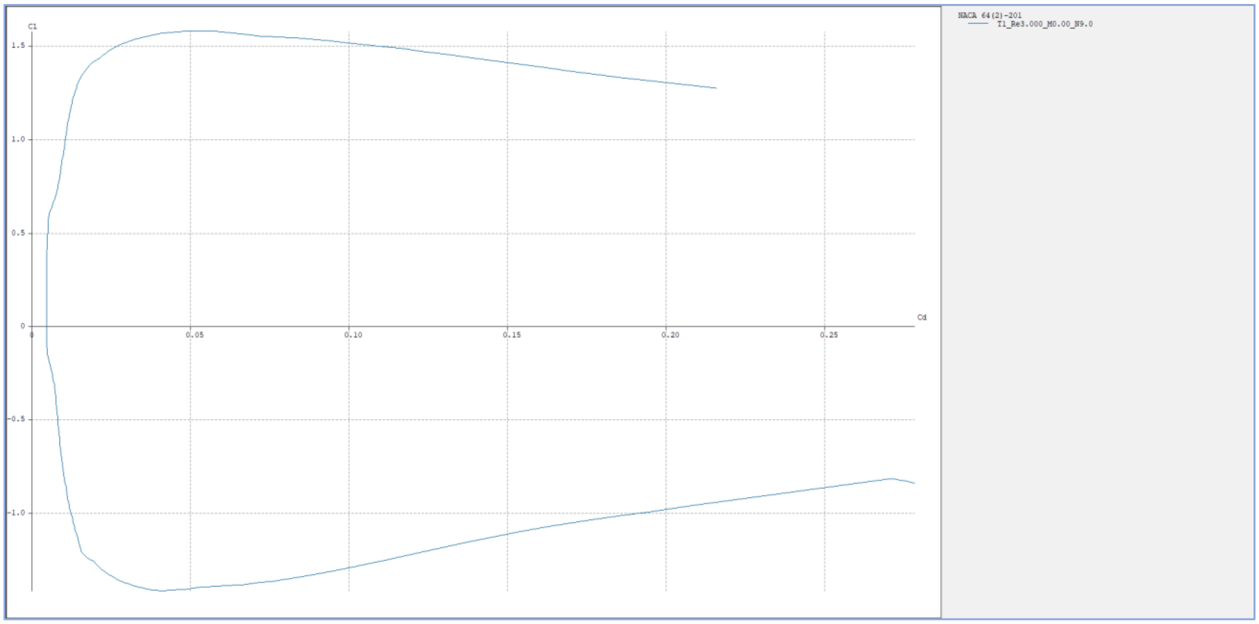
(b) [5 pts.] Plot the lift curve, C_ℓ vs. α (Graph 2). Determine the maximum lift coefficient and the angle of attack where that occurs.



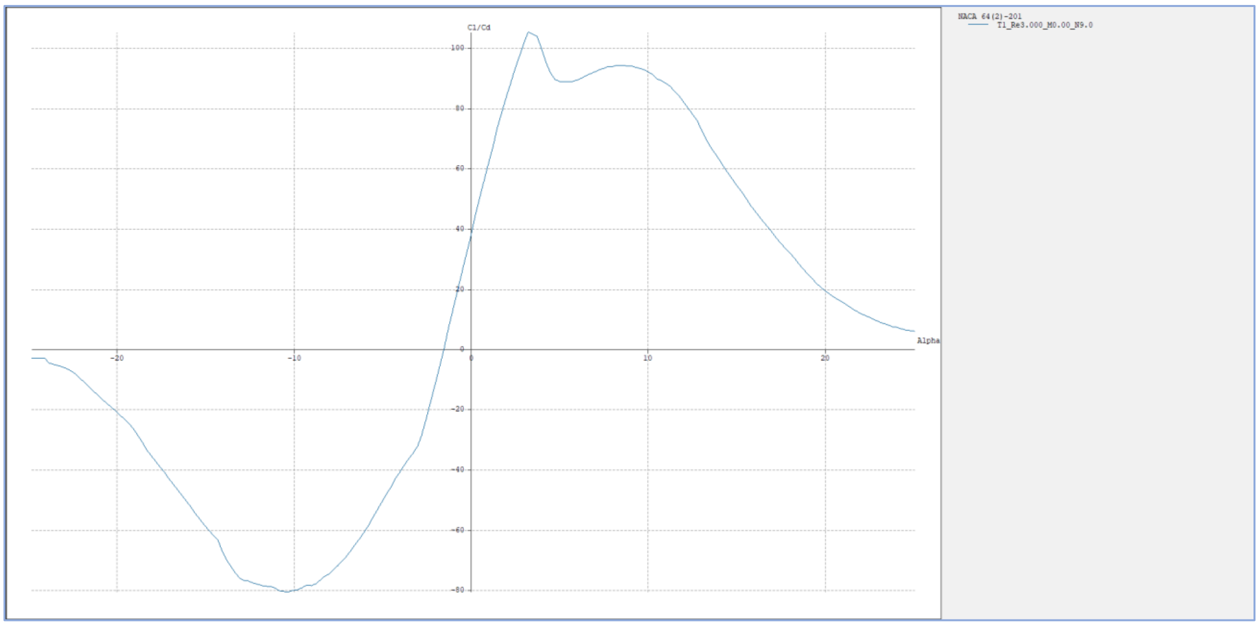
b-1) By exporting the graphical data in XFLR5, and then using the =MAX( ) command in excel we are able to find the maximum life coefficient,

$$\boxed{C_l = 1.577676}$$

(c) [5 pts.] Plot the drag polar, C_ℓ vs. C_d (Graph 1). (Before printing the figure, double click on the graph and reset the axis scales so that you can easily see the drag bucket.)



(d) [5 pts.] Plot the lift to drag ratio, C_ℓ/C_d (Graph 5). Determine the maximum lift to drag ratio, $(L/D)^{max}$, in the following two ways: (i) from the C_ℓ/C_d vs. α plot, and (ii) from the drag polar C_l vs. C_d plot, by drawing a line tangent to the drag polar that also goes through the origin and determining its slope. Note that there is a secondary peak in the lift to drag ratio. On the drag polar printed for part (c), add two dots that correspond to the maximum lift to drag ratio and to this secondary peak. Label the two points (i) and (ii).



d-i) By exporting the data points and using Excel we find that the

First peak (max 1): 105.1151

Second peak (max 2): 94.22602

Since $(\frac{L}{D})max = (\frac{C_l}{C_d})max$

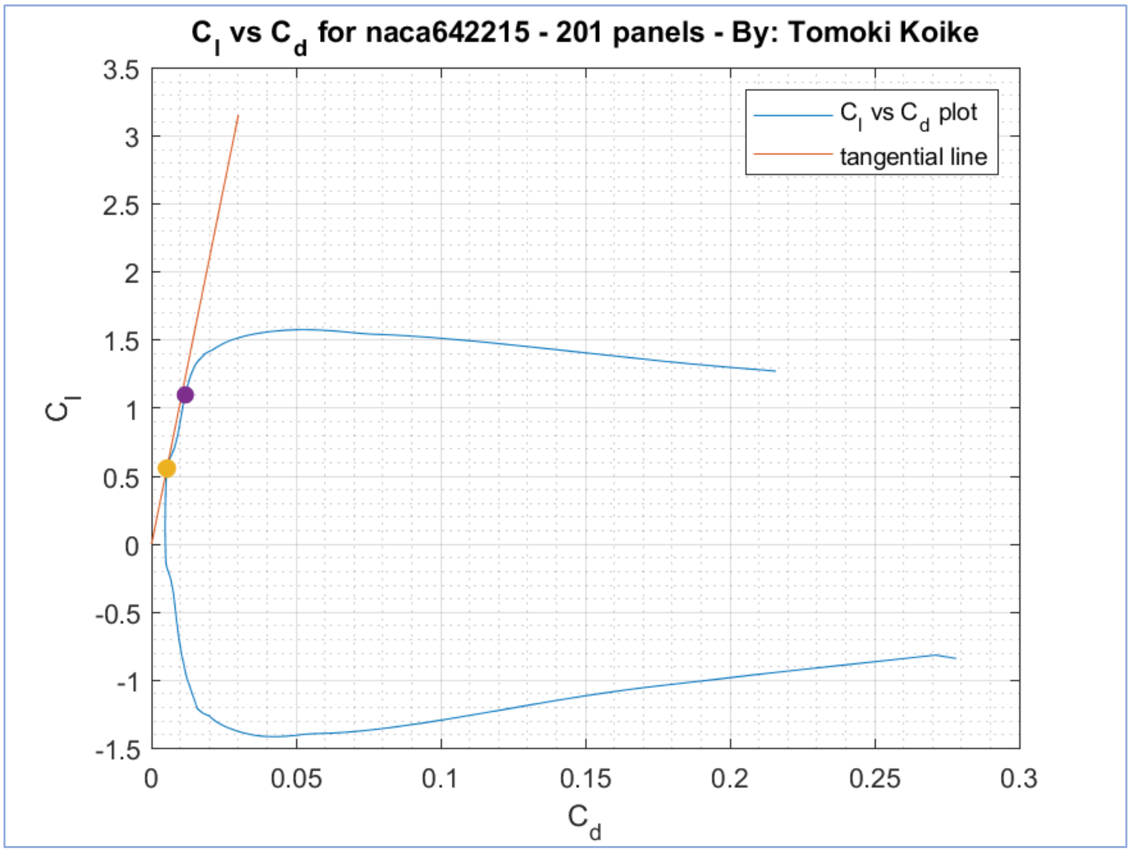
The answer is $\boxed{105.1151}$

d-ii) From the data points exported for the plot in problem c, we take the slope for each data points (x,y) (i.e. y/x) and find the maximum using Matlab (code is in appendix)

The plot looks like the following.

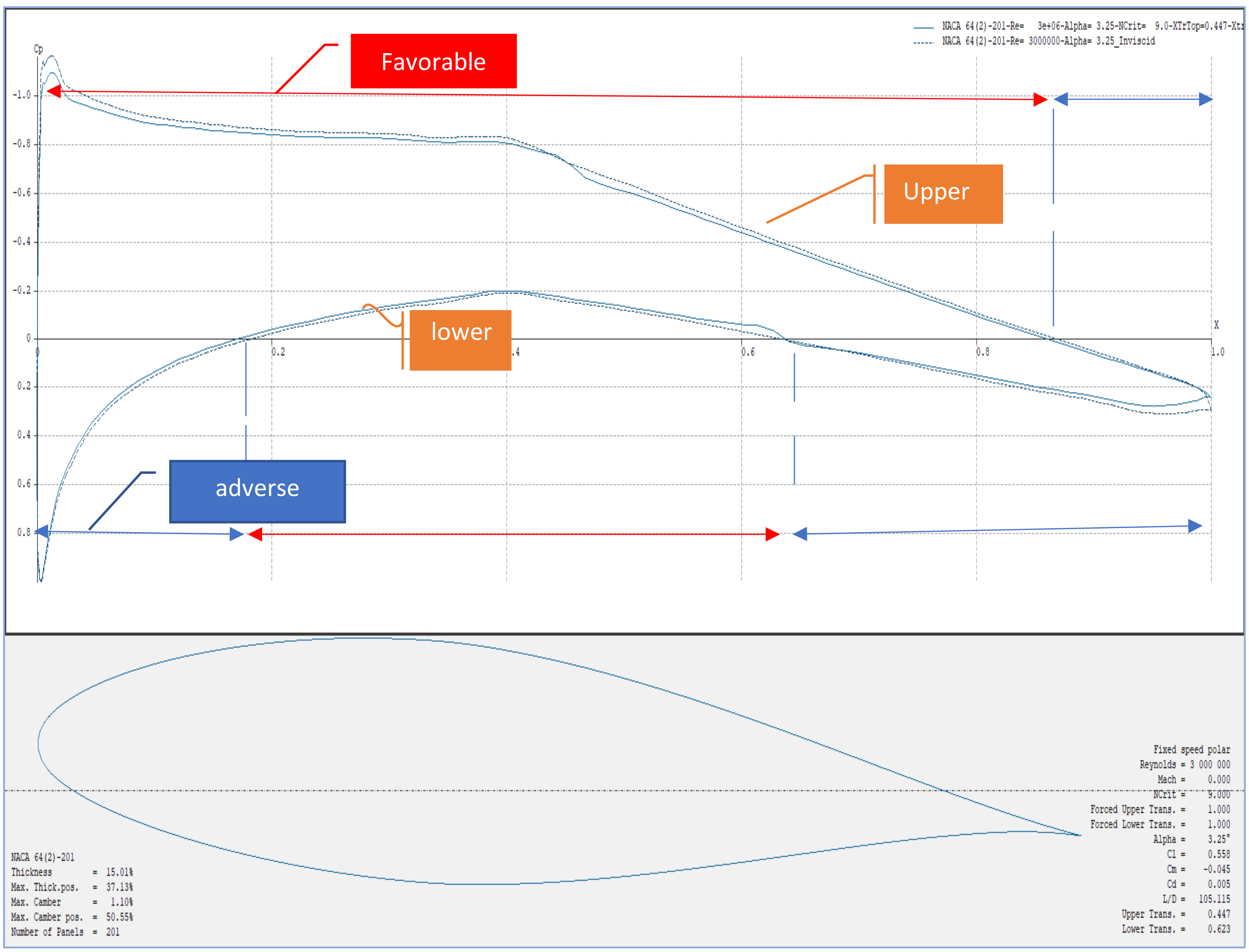
From this method the answer was $\boxed{105.11509}$

d-iii) Find the second peak point with Excel and then plot the instructed line with matlab



(e) [5 pts.] Plot the pressure coefficient distribution, $C_p(x)$, for α equal to the angle with the maximum lift to drag ratio. Include the C_p distribution for inviscid flow. (To do so right click on the C_p plot and choose <`Cp Graph`> <Show Inviscid Curve>.) Mark on the graphs (for just the curves from the viscous analysis) which curves correspond to the upper and lower surfaces. Mark and note in your discussion which regions have a *favorable* pressure gradient and which have an *adverse* pressure gradient. Describe the difference between the C_p distributions from the viscous and the inviscid analyses. Which would give a higher lift coefficient? Where does transition occur on the upper and lower surfaces? (See `Upper Trans.` and `Lower Trans.` in the data presented in the lower right of the C_p window where the airfoil geometry is shown.) Can the transition location be seen in the plot of the pressure distribution?

e) From MATLAB we can find the local maxima and from that we can find the corresponding angle of attack value for the maximum Cl/Cd value with index searching (code provided in appendix). This angle of attack is 3.25^0.

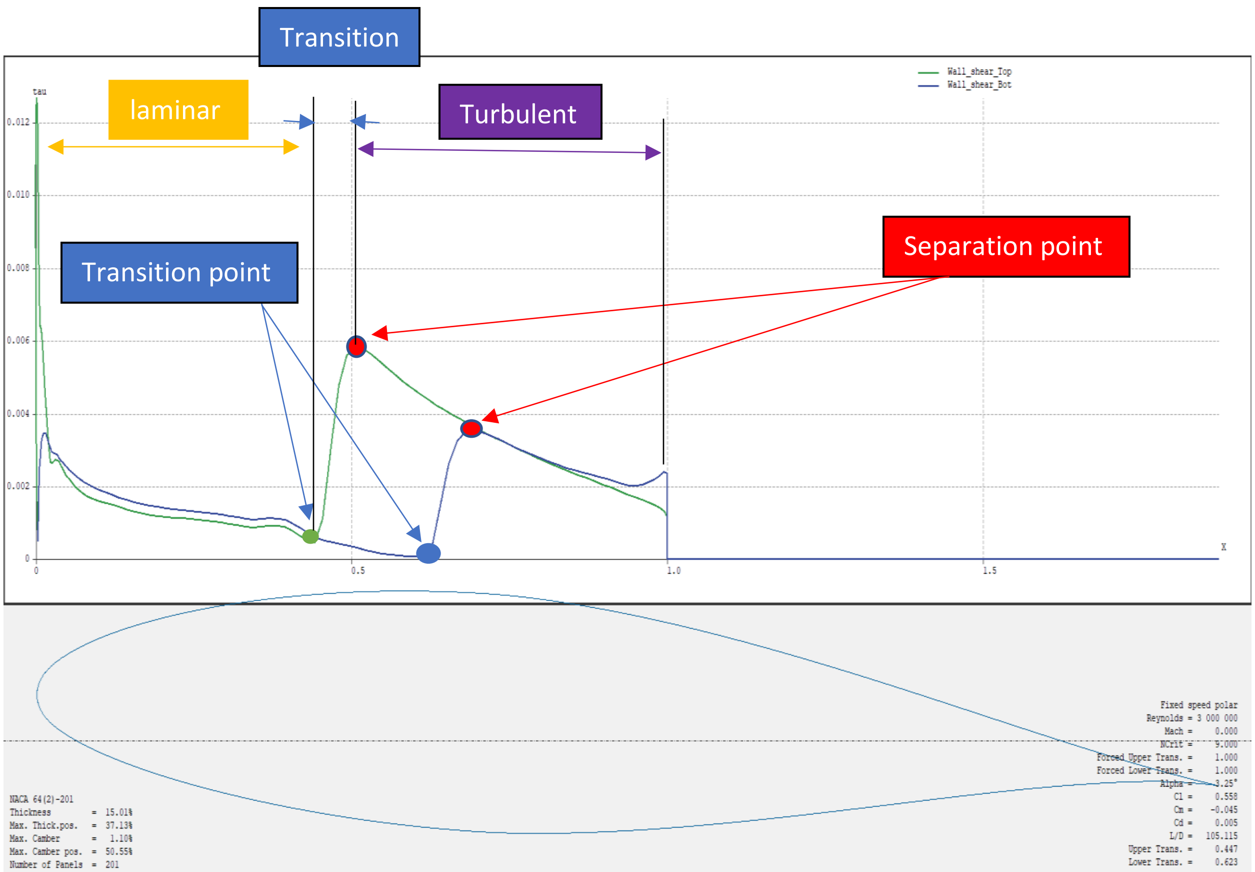


From observing the plot above we can tell that the inviscid flow yields a pressure distribution with more regions of favorable pressure distributions. Therefore, since we know that the lift coefficient can be analytically calculated as a function of the pressure distribution we can say that the inviscid flow will have a higher lift coefficient than the viscous flow.

```
            Fixed speed polar
        Reynolds = 3 000 000
            Mach =     0.000
           NCrit =     9.000
Forced Upper Trans. =  1.000
Forced Lower Trans. =  1.000
           Alpha =     3.25°
              Cl =     0.558
              Cm =    -0.045
              Cd =     0.005
             L/D =   105.115
    Upper Trans. =     0.447
    Lower Trans. =     0.623
```

The lower transition can be observed in the pressure distribution plot as the point where the negative pressure distribution changes to positive at approximately 0.623. Whereas, we cannot see the upper transition point from the pressure distribution plot.

(f) [5 pts.] Plot the wall shear stress, $\tau_w(x)$, for the same value of α as in part (e). See the XFLR5 instructions to learn how to plot the wall shear stress. Adjust the plot axes to clearly show any locations of separation and transition. (It would be best if you do not include the highest peak in the c_f curve in the figure.) Describe how the wall shear stress varies as the boundary layers develop over the upper and lower surfaces of the airfoil (starting at the front stagnation point). (Note that the blue curve is τ_w for the lower (`Bot`) surface, and the green curve is τ_w for the upper (`Top`) surface.) Note where transition happens on the upper and lower surfaces and mark those on the plots. Do these points coincide with the transition locations noted in part (e)? Does the boundary layer separate (indicated by $\tau_w = 0$)? If so, mark the separation locations (and any reattachment locations) on the plot. Does transition or separation happen first? Are the locations of transition related to separation or reattachment in any way?



The plot above tells us that the upper shear goes up rapidly at the LE and increases at a closer location to the LE than the lower wall shear. The lower wall shear, in the other hand, does not go up rapidly at the LE and also increases its value at a farther point from the LE. Interestingly, the shear goes down abruptly zeros in the last half of the airfoil.

The transition points from the wall shear plot match the points in the plot in problem (c).

Theoretically the separation point is where the wall shear goes to zero, and therefore, the separation point should be at the 0.5 point. However, this is not actually the separation point because in the second half of the chord the flow is completely detached and does not correlate to the shear flow which automatically gives the value of zero. When you look at shear distribution we can see that the flow after the point where the shear shoots up is the turbulent flow and the nearly perpendicular region is the transition flow. Hence, the separation point is the point where the turbulent flow starts, and from this we know that the transition point is before the separation point for both upper and lower surfaces. After the separation point the shear distribution deceases smoothly and there is no reattachment occurring. We know this because if the flow were to reattach the shear distribution should become a negative value and once again increase to a positive value.

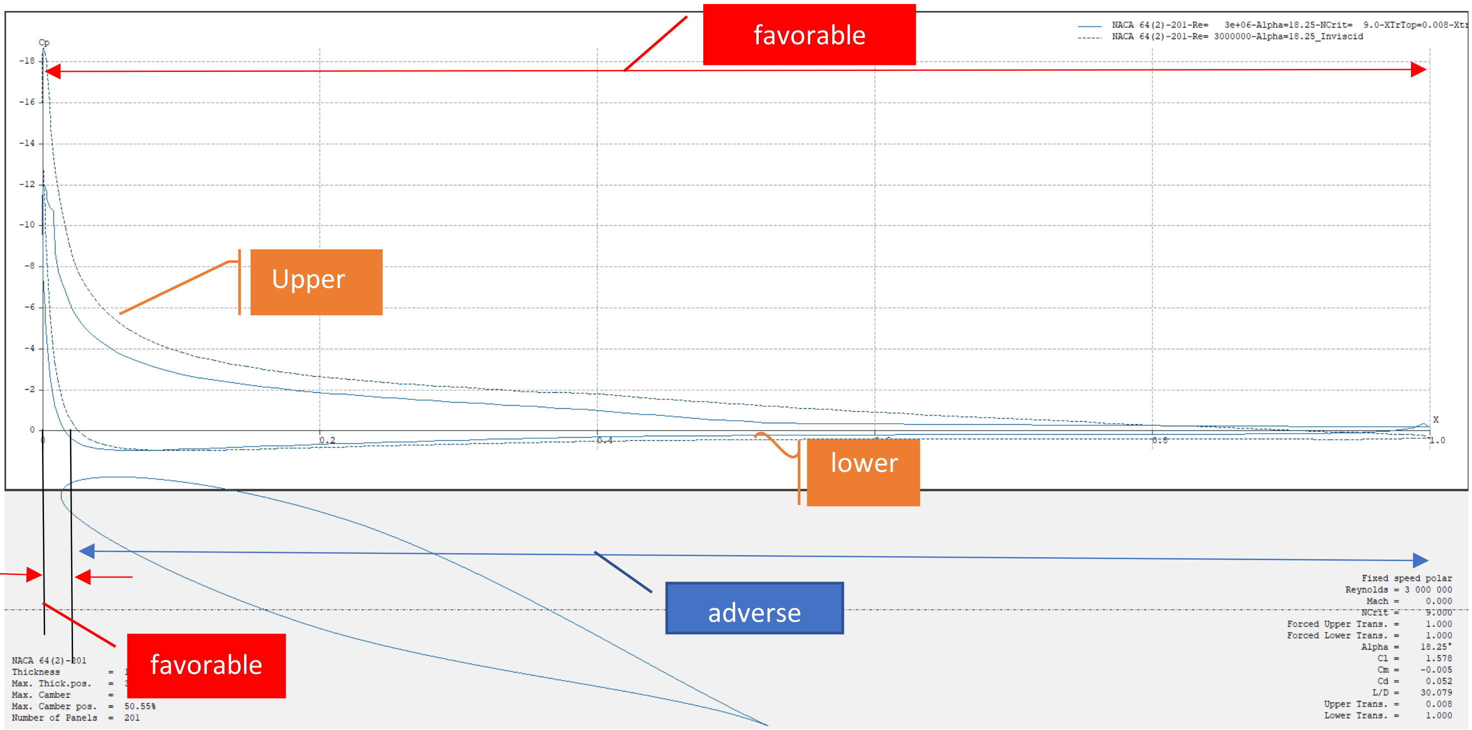
(g) [5 pts.] Tabulate the lift coefficient, c_ℓ; drag coefficient, c_d; and the drag coefficient due to pressure (form drag), c_{dp}, at the angle of attack considered in parts (e) and (f). (To find the value of c_{dp}, as well as more precise values of c_ℓ and c_d, click on <Operating Points> <Current OpPoint> <Properties>.) Also tabulate the percentage of the drag coefficient due to form drag.

Alpha	Cl	Cd	Cdp	Cdp/Cd*100 (%)
0.	0.55781	0.00531	0.00113	21.2806

(h) [15 pts.] Repeat parts (e), (f) and (g) for the angle of attack corresponding to the maximum lift coefficient.

Using MATLAB we find that the angle of attack corresponding with the maximum lift coefficient is

Alpha = 18.25^0

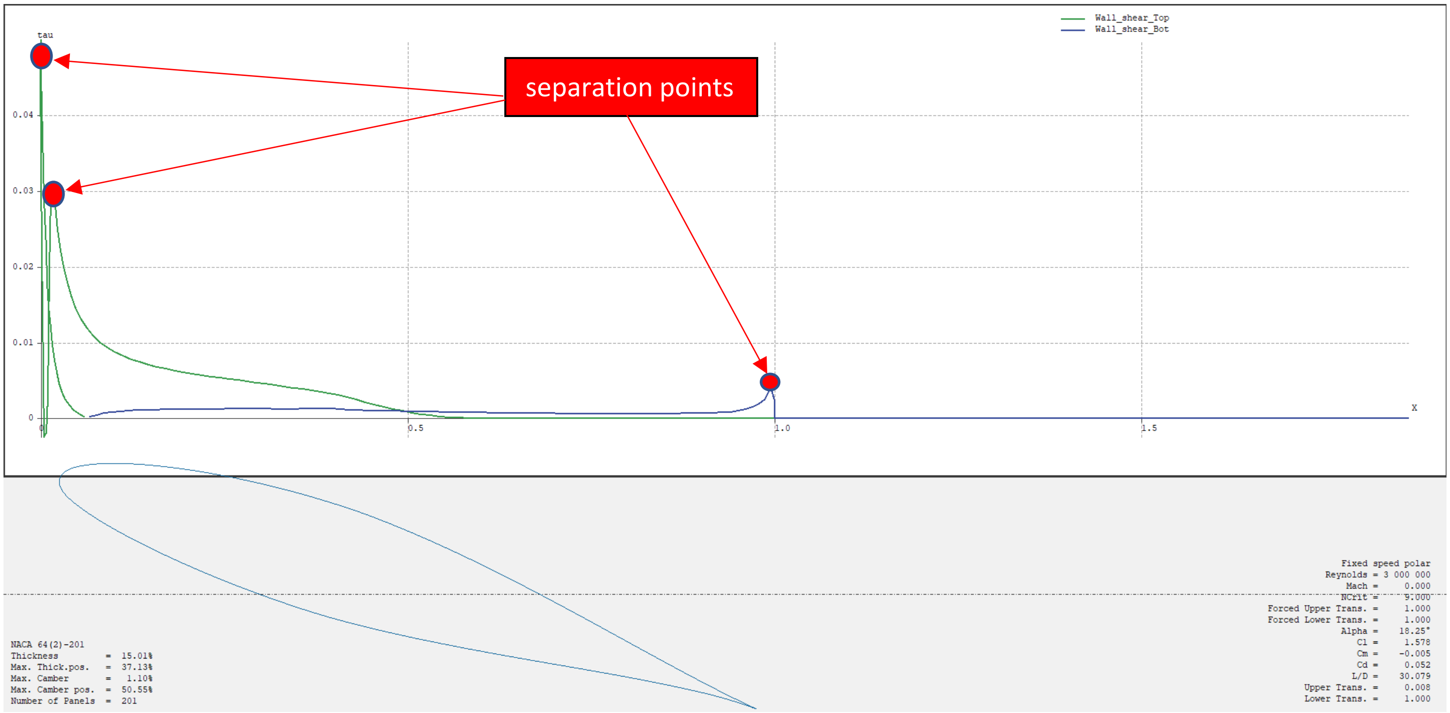


For this plot, the inviscid pressure distribution has a very higher pressure distribution at the LE for the upper surface. Besides this difference the inviscid agrees with the pressure distribution for the viscous flow. Since the pressure distribution for the inviscid flow is considerably larger than the viscous flow the inviscid flow will yield a higher life coefficient.

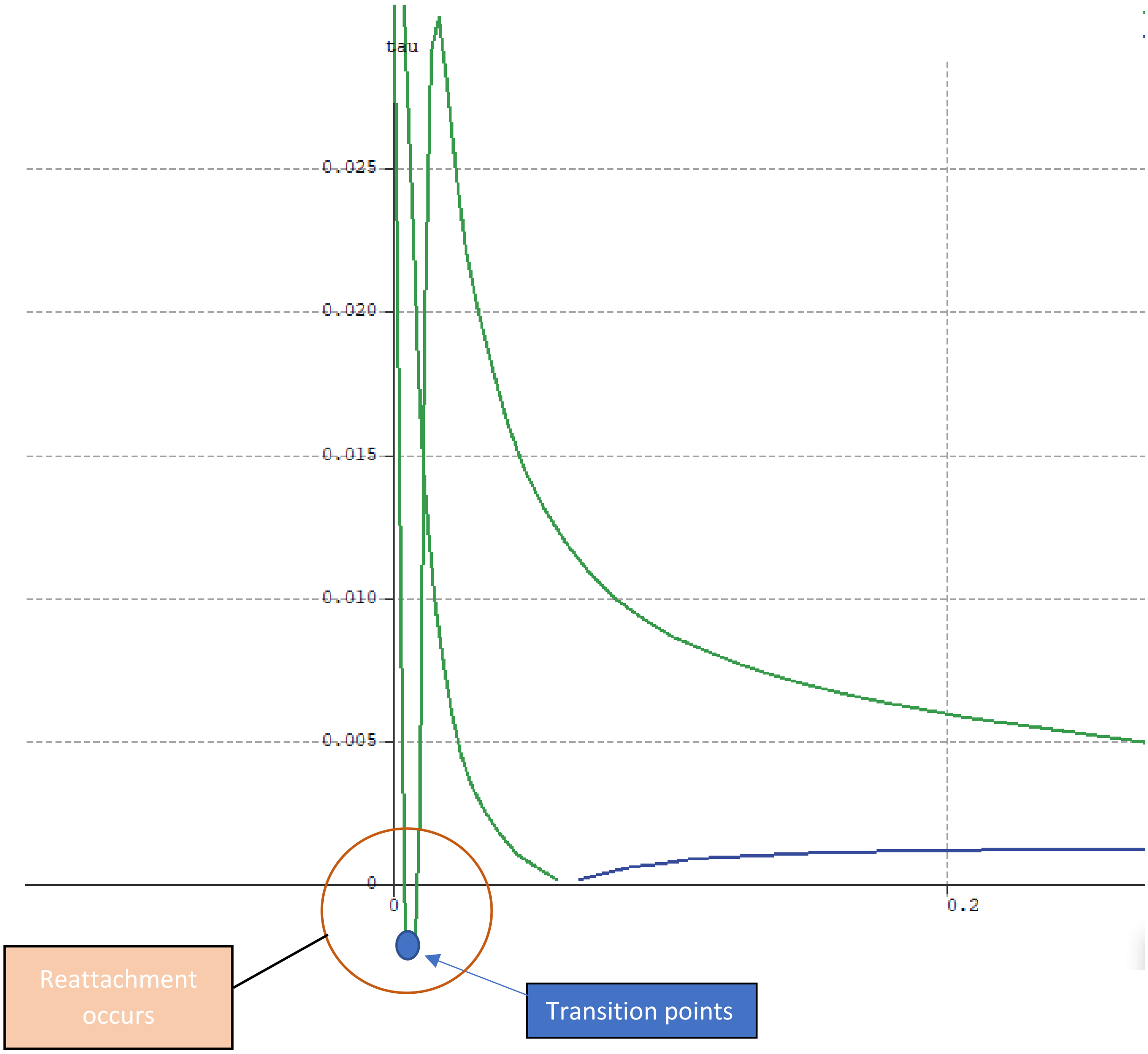
Fixed speed polar

Reynolds =	3 000 000
Mach =	0.000
NCrit =	9.000
Forced Upper Trans. =	1.000
Forced Lower Trans. =	1.000
Alpha =	18.25°
Cl =	1.578
Cm =	-0.005
Cd =	0.052
L/D =	30.079
Upper Trans. =	0.008
Lower Trans. =	1.000

Since the transition point for the upper surface is too small it is hard to observe the exact point on the distribution plot. The lower bound seems to have an intersecting point near the LE edge but this seems to not be the transition point. However, we can tell that the TE is the transition point for the lower surface from the plot.



For this wall shear distribution on the upper surface fluctuates in the proximity of the LE because of the transition and separation points being very close to the LE. Whereas, the shear at the lower surface has overall a very small wall shear which has a curve with a small incremental gradient until the half chord length with a short and small transition process.



For the upper surface the transition point coincides with that of the pressure distribution, however, the lower surface does not.

Yes, the boundary layer separates. And from the marks we can tell that the separation occurs before the transition. Also for the upper surface there is a point where the distribution dips to the negative side and reenters the positive side. This indicates the existence of a reattachment occurring for the upper surface.

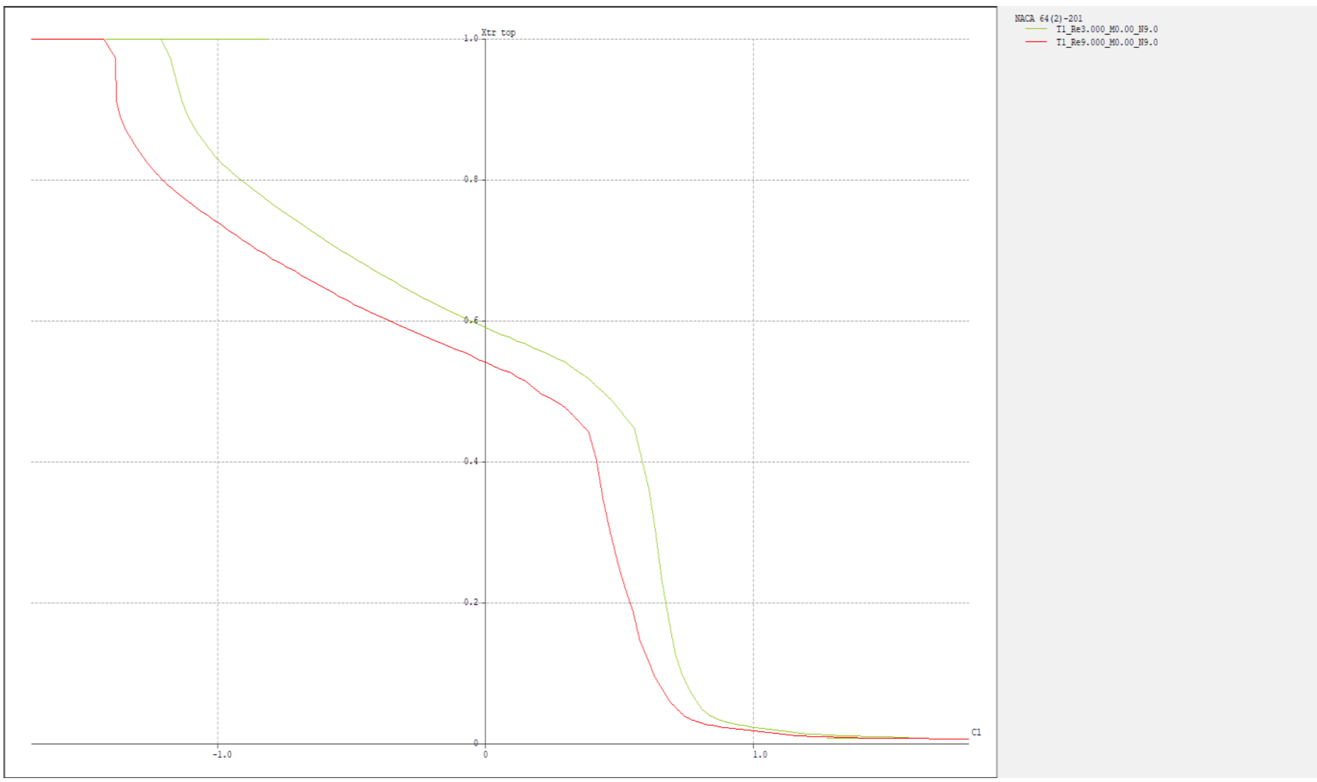
Alpha	Cl	Cd	Cdp	Cdp/Cd*100 (%)
18.25	1.57768	0.05245	0.04847	92.4118

(i) [5 pts.] Discuss the trends found in the form drag with changes in angle of attack based on the tabulated data.

From the tabulated data we know that at high angle of attacks the percentage of the form drag becomes substantially larger than when the angle of attack is small. This is depicted for the two angles we have analyzed: 0.325 and 18.25. When the angle of attack is small this means that the amount of skin friction accounts for most of the drag on the airfoil.

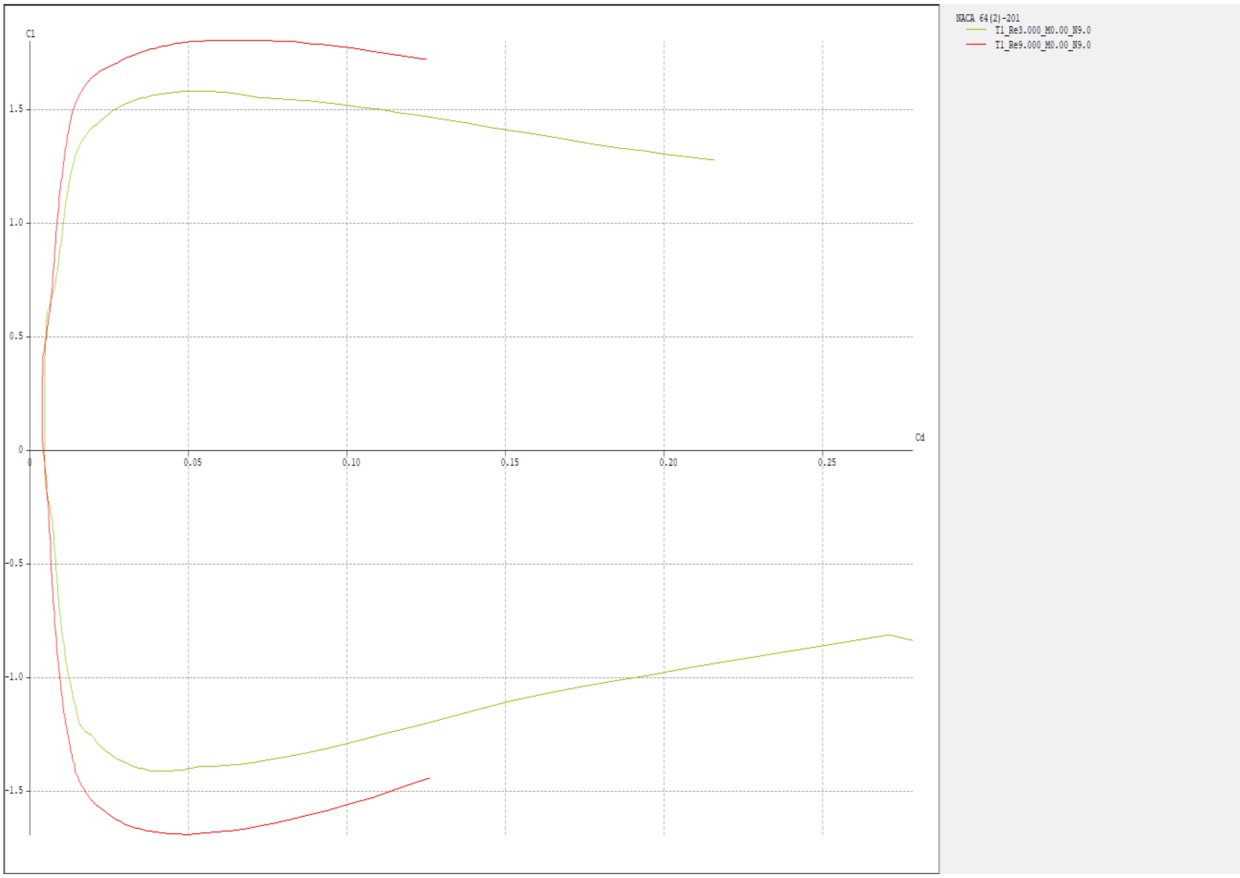
[35 pts.] 2. Perform a new XFLR5 analysis for the airfoil used in problem 1 with 201 panels for a value of Reynolds number $Re = 3 \times 10^6$ for $\alpha = -25^\circ$ to $\alpha = 25^\circ$. Then repeat the analysis with Reynolds number $Re = 9 \times 10^6$. XFLR5 will keep track of both sets of results and plot them as different colored curves in the polar graphs. (If you need to set the color to distinguish the two cases, you can select the color in the `Graph Curve Settings` in the lower right corner.)

(a) [5 pts.] Plot `Graph 4`, the transition location on the upper surface, x_{tr}, vs. lift coefficient. Describe what happens to the transition location as the angle of attack is increased. Describe how the transition location is affected by Reynolds number.



As the angle of attack increases the transition point on the upper surface decreases, and within the range of negative small angle of attacks the decrease rate is slower than the range of positive small angle of attacks.

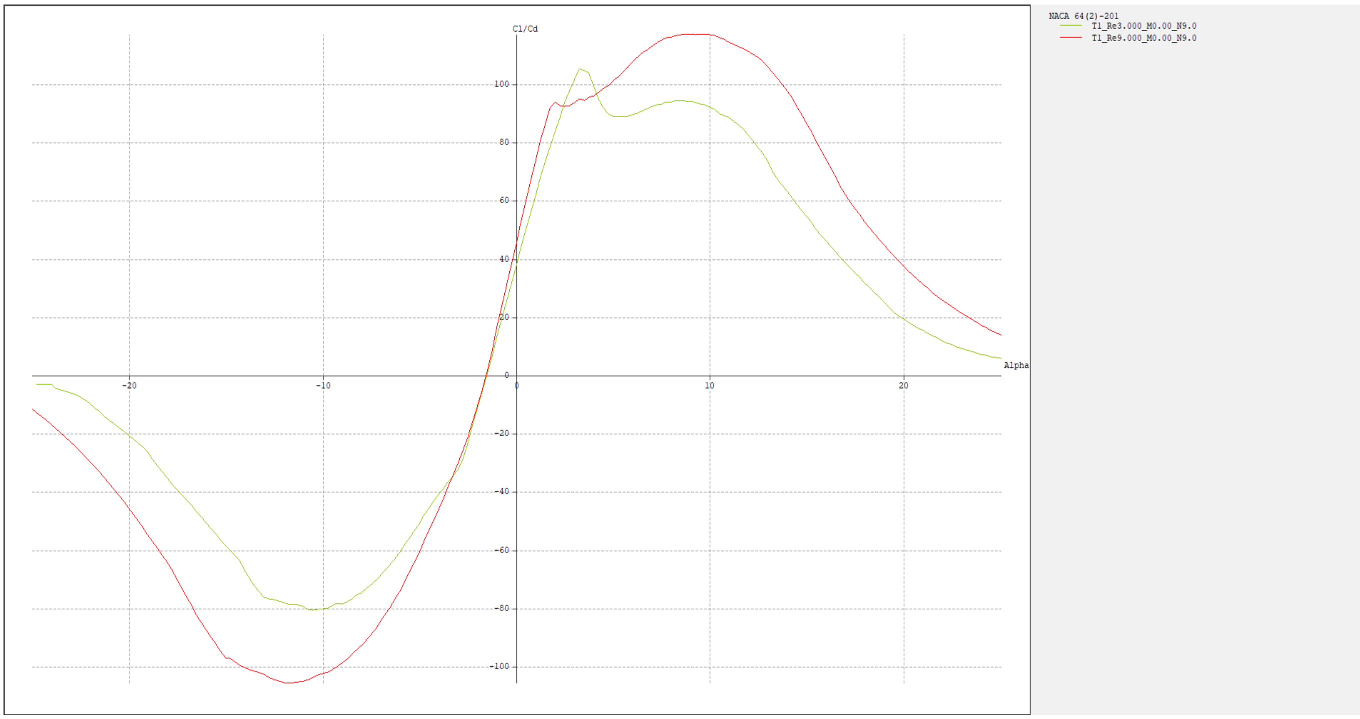
(b) [5 pts.] Plot **Graph 1**, the drag polar. Adjust the axis limits so that the drag bucket is easily seen. How does Reynolds number affect the width of the drag bucket? Does the trend seen make sense, given the results of part (a)? Explain.



For this plot the Reynolds number equal to 9M (red) has a larger lift coefficient because of the increase in velocity and when the Reynolds number is higher the drag coefficient has a lower maximum value than the Reynolds number of 3M.

This is explainable because to make the Reynolds number larger the viscosity becomes smaller, the velocity becomes larger, or the object becomes larger. The former two reasons pander with the logic that to have lower drag the boundary layer has to remain attached to object. Thus, with higher Reynolds number the lift coefficient becomes overall larger and the drag coefficient becomes lower.

(c) [5 pts.] Perform a similar analysis to part (d) from problem 1 for the drag polar and lift to drag ratio plots you have here for the two values of Reynolds numbers. Discuss how the results are affected by Reynolds number.



Using Excel from the exported data points from the plot above we get (for only 9M Reynolds number since 3M Reynolds number is the exact same analysis in problem 1)

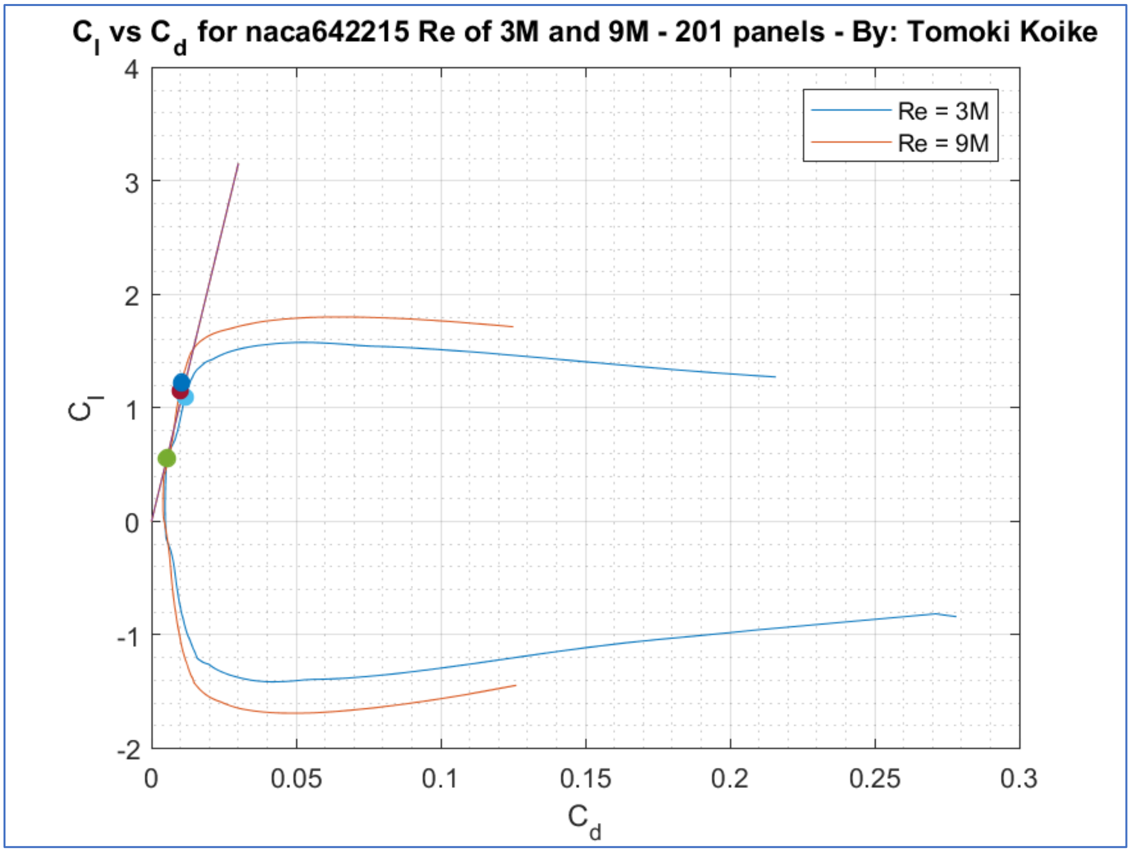
peak (max): 116.9899

Since $(\frac{L}{D})_{max} = (\frac{C_l}{C_d})_{max}$

The answer is $\boxed{116.9899}$

Drawing a tangential line and calculating the L/D maximum ratio with MATLAB we get (for 9M Reynold number)

Maximum is $\boxed{116.9898}$

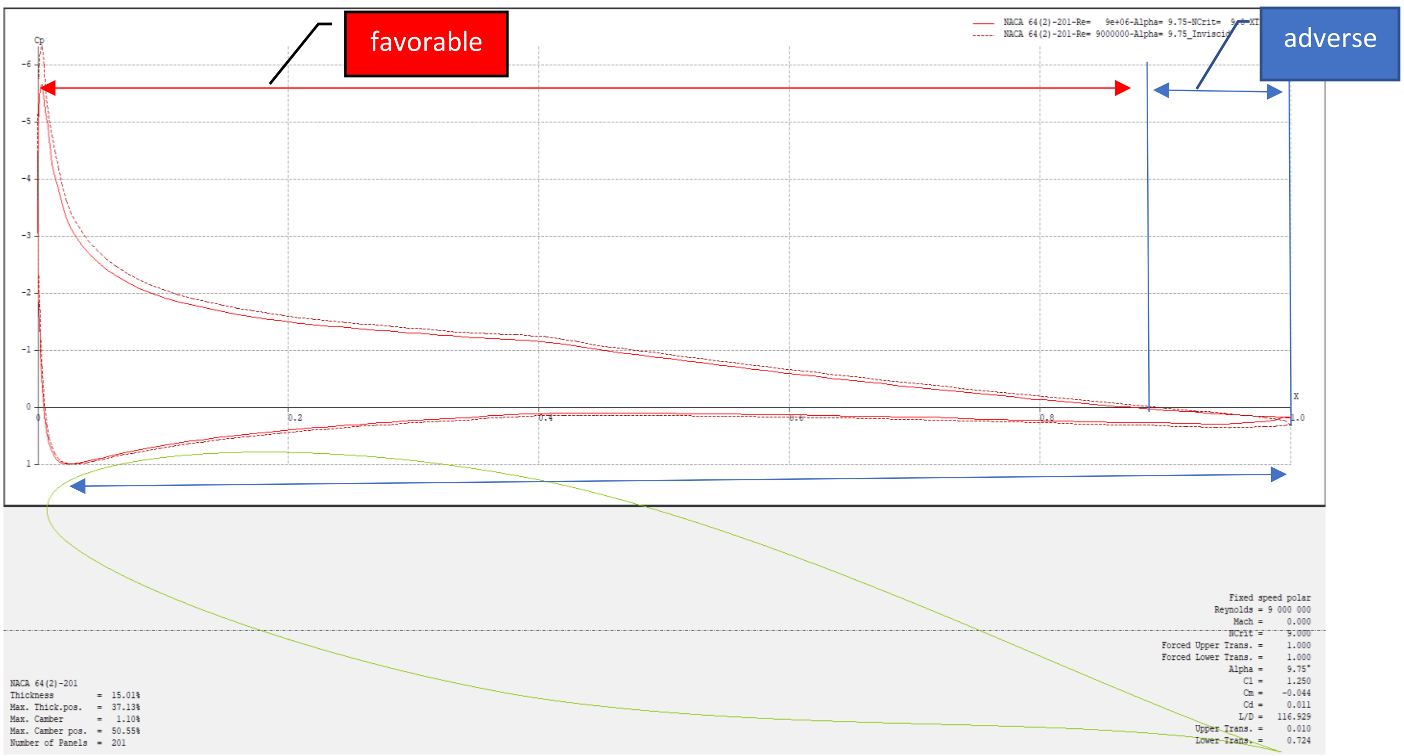


C_l vs C_d for naca642215 Re of 3M and 9M - 201 panels - By: Tomoki Koike
Re = 3M
Re = 9M
C_l
C_d
4
3
2
1
0
-1
-2
0
0.05
0.1
0.15
0.2
0.25
0.3

(d) [5 pts.] Perform a similar analysis to part (e) from problem 1, but at a value of Reynolds number of $Re = 9 \times 10^6$. Compare the pressure coefficient plot to that found in problem 1 and describe the differences in the C_p distributions at the maximum lift to drag ratio condition at these two Reynolds numbers. (Note that the angles of attack are different for the two cases.)

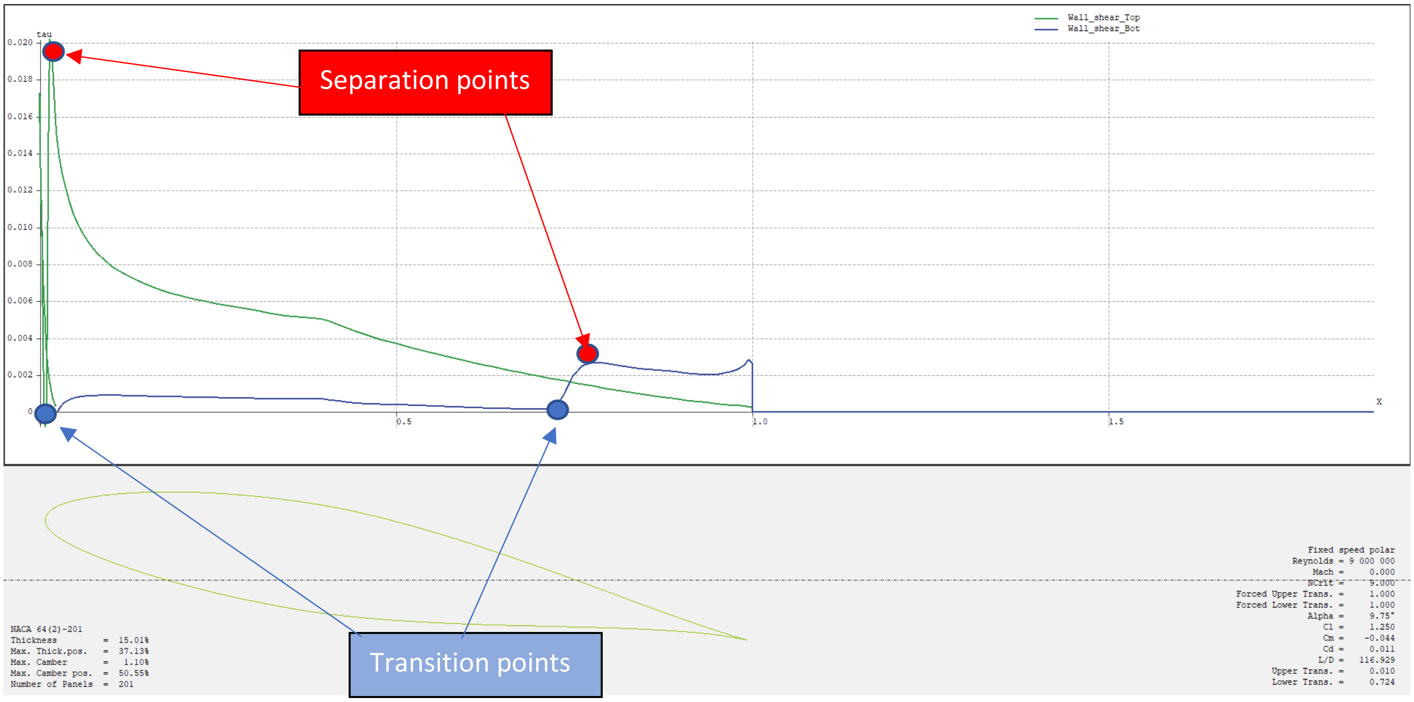
The angle of attack at maximum lift over drag ratio for Re = 9M is (calculated from MATLAB)

Alpha = 9.75^0



When the Reynolds number is 9M the lower surface is overall adverse. At the upper surface the pressure distribution is overall favorable but just at the proximity of the TE, the flow becomes adverse with a positive pressure gradient.

(e) [5 pts.] Perform a similar analysis to part (f) from problem 1, but at a value of Reynolds number of $Re = 9 \times 10^6$. Compare the skin friction coefficient plot to that found in problem 1 and describe the differences in the c_f distributions at the maximum lift to drag ratio condition at these two Reynolds numbers. (Note that the angles of attack are different for the two cases.)

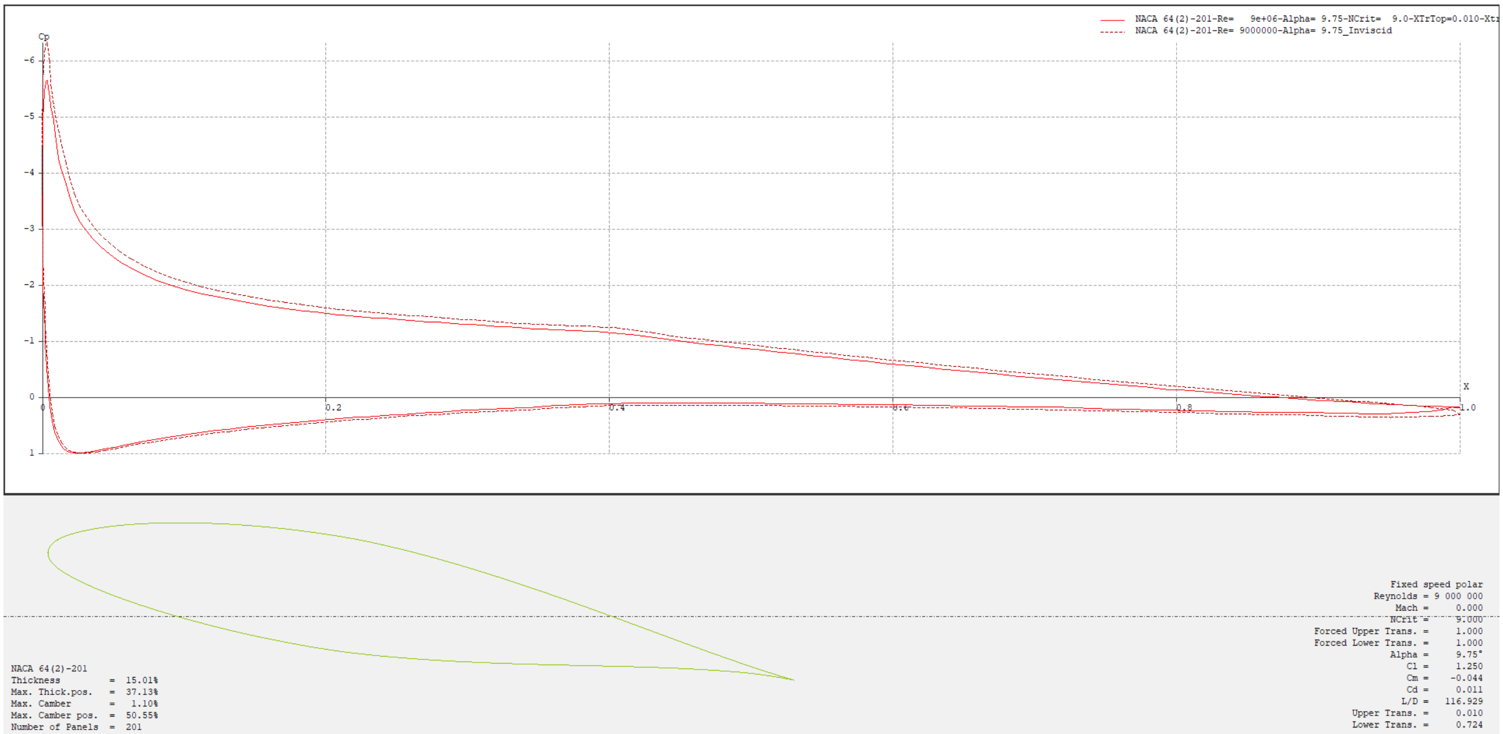


For the Reynolds number of 9M the shear distribution is very different from that of 6M and at the angle of maximum L/D. This is closer to when the angle of attack is high for Reynolds number of 6M. The upper surface undergoes transition and separation at a position very close to the LE and reattaches after it separates once. The lower surface has a trend similar to Reynolds number of 6M. The transition point is a 0.75 of the chord length and transitions smoothly to turbulent flow. Most importantly the deviation between the upper and lower surface is substantial compared to the plot in problem 1 (f).

(f) [10 pts.] Repeat parts (d) and (e) (of this problem) for the maximum lift coefficient angle of attack. Make comparisons with the corresponding results from problem 1.

The angle with maximum angle of attack is computed in MATLAB as

Alpha = 21.75°



For this plot the deviation between the upper and lower surface is larger than that of Reynolds number of 3M. For the upper surface close to half-chord the pressure decrease rate goes down somewhat which was not observed in the previous observation in problem 1. Also, the distribution on the lower surface curves in a concave downwards manner which was something not seen as well. Besides those characteristics the pressure distribution is somewhat similar.

Interestingly for the Reynolds number 9M shear distribution the distribution is not so different from the angle of attack of 9.75 where the L/D is maximum. In the plot above the transition and separation points for the upper surface remains at a close location to the LE and the transition point for the lower surface also has not changed. This means that with the low viscosity or high velocity (which makes the Reynolds number high) the shear distribution does not change that much based on the angle of attack.

But compared to the 3M Reynolds number condition the shear in the range marked with an orange arrow remains higher.

problem 1

```
clear all; close all; clc;
```

(d)

```
% Import data as matrix
Cl_vs_Cd = readtable('p1_c_Cl_vs_Cd.csv');  % Read file
Cl_vs_Cd = table2array(Cl_vs_Cd);  % convert table to array
Cl = Cl_vs_Cd(:,2);  % Assign Cl values
Cd = Cl_vs_Cd(:,1);  % Assign Cd values
dydx = Cl./Cd;  % Find the gradient of each points
[max_Cl_over_Cd, idx] = max(dydx)
Cd_idx = Cd(idx)
Cl_idx = Cl(idx)
% Tangential line
x = linspace(0,0.03);
y = Cl_idx/Cd_idx.*x;
```

```
% Finding local maximums
Cl_over_Cd_vs_AoA = csvread('p1_d_Cl_over_Cd_vs_AoA.csv');
Cl_over_Cd = Cl_over_Cd_vs_AoA(:,2);
AoA1 = Cl_over_Cd_vs_AoA(:,1);
local_max_idx = islocalmax(Cl_over_Cd);
local_max_Cl = Cl(local_max_idx);
local_max_Cd = Cd(local_max_idx);
local_max_AoA = AoA1(local_max_idx)
```

```
% Plotting
fig1 = figure('Renderer','painters');
plot(Cd, Cl)
title('C_l vs C_d for naca642215 - 201 panels - By: Tomoki Koike')
xlabel('C_d')
ylabel('C_l')
hold on
plot(x,y)
plot(local_max_Cd(3), local_max_Cl(3),'.','MarkerSize',20)
plot(local_max_Cd(4), local_max_Cl(4),'.','MarkerSize',20)
hold off
legend('C_l vs C_d plot', 'tangential line')
```

```
grid on
grid minor
box on
saveas(fig1, 'p1_d_tangential_line.png')
```

<h>

```
[max_Cl, idx2] = max(Cl)
AoA_maxCl = AoA1(idx2)
```

problem 2

```


% Import data as matrix
Cl_vs_Cd_new = readtable('p2_c_Cl_vs_Cd.csv');  % Read file
Cl_vs_Cd_new = table2array(Cl_vs_Cd_new);  % convert table to array
Cl3 = Cl_vs_Cd_new(:,2);  % Assign Cl values
Cd3 = Cl_vs_Cd_new(:,1);  % Assign Cd values
dydx3 = Cl3./Cd3;  % Find the gradient of each points
[max_Cl_over_Cd3, idx3] = max(dydx3)
Cd_idx3 = Cd3(idx3)
Cl_idx3 = Cl3(idx3)
% Tangential line
x3 = linspace(0,0.03);
y3 = Cl_idx3/Cd_idx3.*x3;


Cl9 = Cl_vs_Cd_new(:,4);  % Assign Cl values
Cd9 = Cl_vs_Cd_new(:,3);  % Assign Cd values
dydx9 = Cl9./Cd9;  % Find the gradient of each points
[max_Cl_over_Cd9, idx9] = max(dydx9)
Cd_idx9 = Cd9(idx9)
Cl_idx9 = Cl9(idx9)
% Tangential line
x9 = linspace(0,0.03);
y9 = Cl_idx/Cd_idx.*x3;
```

```
% Finding local maximums
% 3M
Cl_over_Cd_vs_AoA_new = csvread('Polar_Graph_4.csv');
Cl_over_Cd3 = Cl_over_Cd_vs_AoA_new(:,2);
AoA3 = Cl_over_Cd_vs_AoA_new(:,1);
local_max_idx3 = islocalmax(Cl_over_Cd3)
local_max_Cl3 = Cl3(local_max_idx3)
local_max_Cd3 = Cd3(local_max_idx3)
```

```
local_max_AoA3 = AoA3(local_max_idx3)
% 9M
Cl_over_Cd9 = Cl_over_Cd_vs_AoA_new(:,4);
AoA9 = Cl_over_Cd_vs_AoA_new(:,3);
local_max_idx9 = islocalmax(Cl_over_Cd9)
local_max_Cl9 = Cl9(local_max_idx9)
local_max_Cd9 = Cd9(local_max_idx9)
local_max_AoA9 = AoA9(local_max_idx9)
```

```
% Plotting
fig2 = figure('Renderer','painters');
plot(Cd3, Cl3)
title('C_l vs C_d for naca642215 Re of 3M and 9M - 201 panels - By: Tomoki
Koike')
xlabel('C_d')
ylabel('C_l')
hold on
plot(Cd9,Cl9)
plot(x9,y9)
plot(x3,y3)
plot(local_max_Cd3(3), local_max_Cl3(3),'.','MarkerSize',20)
plot(local_max_Cd3(4), local_max_Cl3(4),'.','MarkerSize',20)
plot(local_max_Cd9(3), local_max_Cl9(3),'.','MarkerSize',20)
plot(local_max_Cd9(4), local_max_Cl9(4),'.','MarkerSize',20)
hold off
legend('Re = 3M', 'Re = 9M')
grid on
grid minor
box on
saveas(fig2, 'p2_d_tangential_line.png')
```

```
[max_Cl9, idx_oho] = max(Cl9)
AoA_maxCl9999 = AoA9(idx_oho)
```