CITY COLLEGE

CITY UNIVERSITY OF NEW YORK

Assignment #1

ME 572: Aerodynamic Design

Fall 2011

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Wind Tunnel Measurement around NACA 2415

Submitted By:

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Nomenclature

$X = x - coordinate\ of\ position\ along\ the\ Airfoil$

$Y = y - coordinate\ of\ position\ along\ the\ Airfoil$

$C_l = Coefficient\ of\ Lift$

$C_D = Coefficients\ of\ Drag$

$C_{m_{LE}} = Coefficients\ of\ moment$

$C_{p_l} = Pressure\ coefficient\ at\ lower\ level$

$C_{p_U} = Pressure\ coefficient\ at\ Upper\ level$

$C_{f_L} = Friction\ coefficient\ at\ lower\ level$

$C_{F_U} = Friction\ coefficient\ at\ Upper\ level$

$C = chord\ length$

$\frac{dY_u}{dX} = slope\ of\ airfoil\ upper\ level$

$\frac{dy_L}{dx} = slope\ of\ airfoil\ lower\ level$

$\alpha = angel\ of\ attack$

• Abstract

The purpose of this project is to do the post analysis of the experimental data of wind tunnel experiment of NACA 2415 airfoil and calculate the coefficient of drag, lift and moment using the numerical method and comparing the result with external resources.

• Introduction

An airfoil is any surface, such as a wing or rotor blade, designed to produce lift when air passes over it. Air passing over the upper surface of a foil produces a lower pressure under the airfoil produces the higher pressure of air on the foil's surface, as shown in figure 1.0.

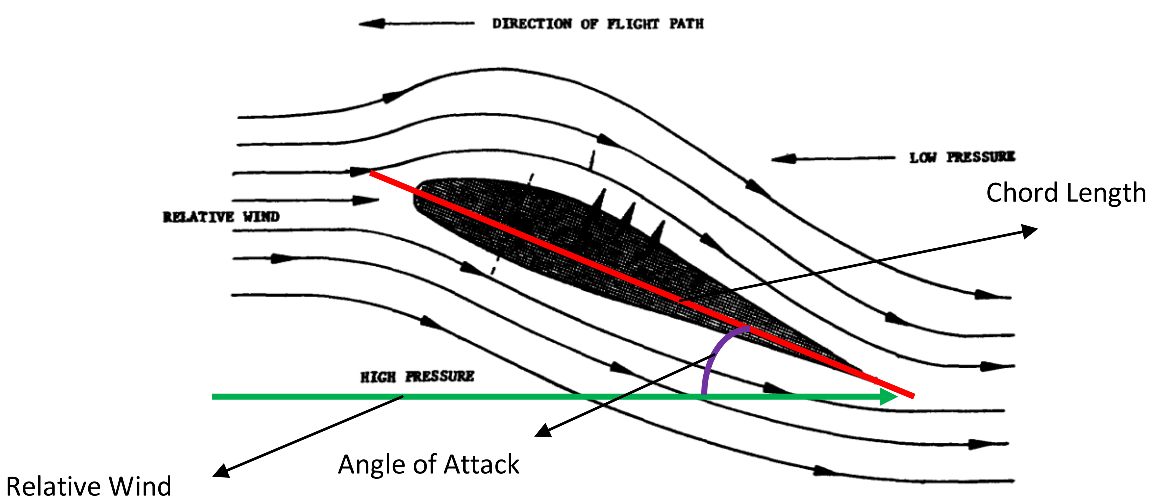


Figure 1.0

A symmetrical airfoil is a foil which has equal cambers on both sides. This kind of airfoil has the characteristics of limiting center-of-pressure travel. An asymmetrical airfoil is designed to have unequal cambers. This type of airfoil has the characteristic of a rapid movement of center-of-pressure travel.

The angle of attack is the angle at which an airfoil passes through the air. This angle is measured between the chord of the airfoil and the relative wind, as shown in figure 1.0. The chord is an imaginary line from the leading edge to the trailing edge of an airfoil. Increasing the angle of attack deflects the airstream and causes an upward pressure on the underside of the airfoil. This in turn increases the speed of the airflow over the topside of the airfoil. As air-flow-speed increases, pressure on the foil's top side is further reduced which furnish the lift upward in this case.

• Evaluation and Discussion

1) Outline of the airfoil

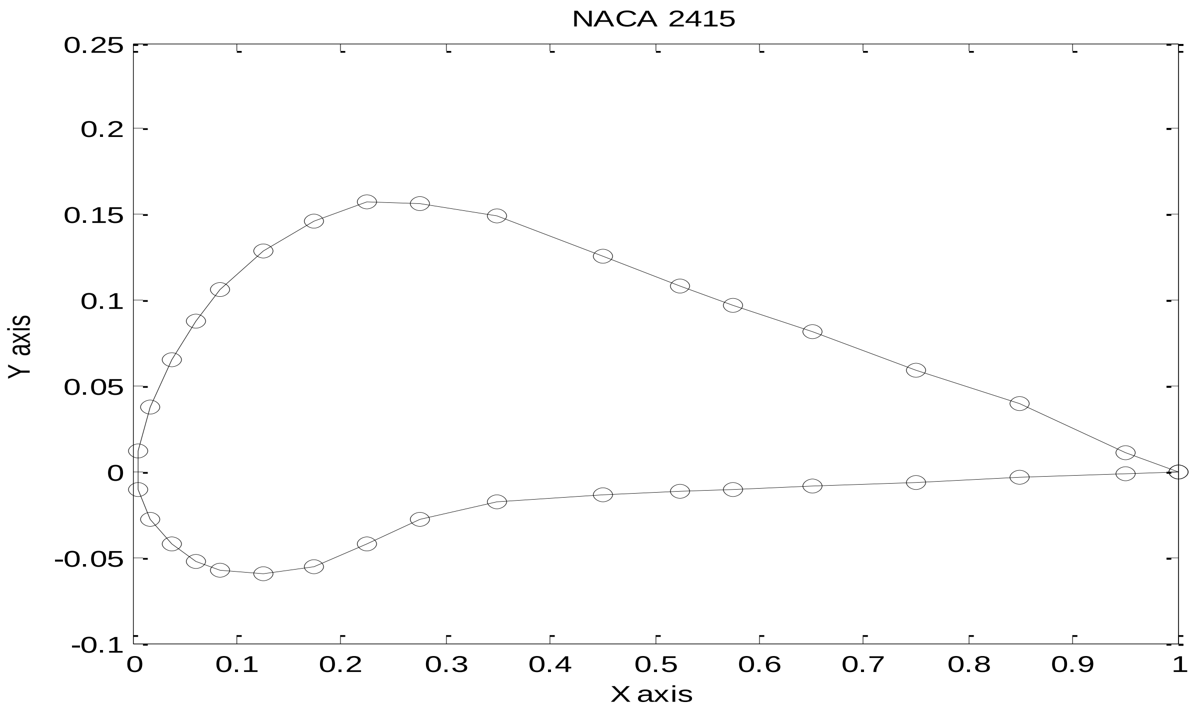


Figure 2.0 The outline of the airfoil NACA 2415

NACA 2415

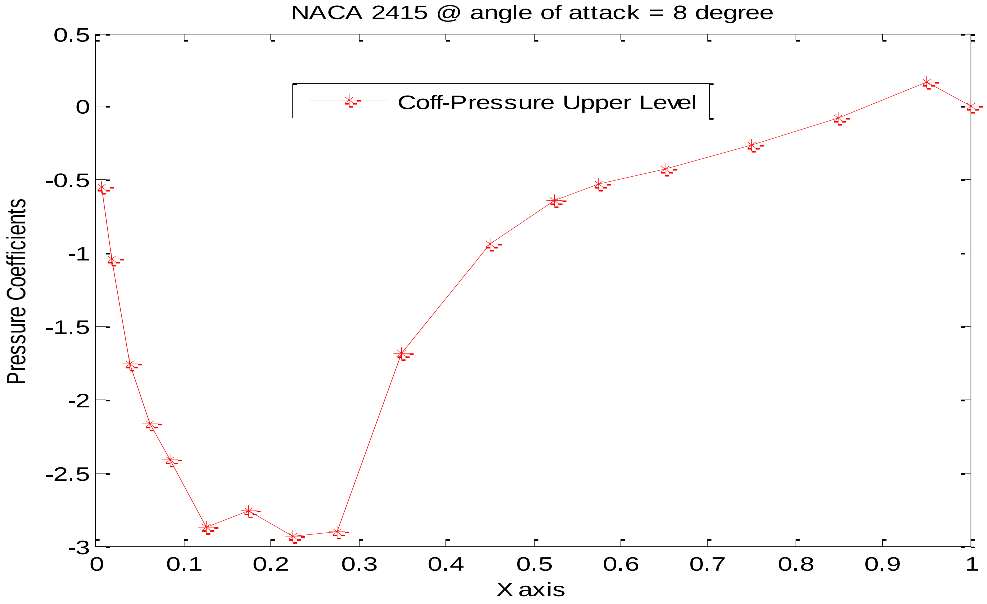
2 - The maximum camber of the mean line is 0.02c. (first digit)

4 - The position of the maximum camber is at 0.4c. (second digit)

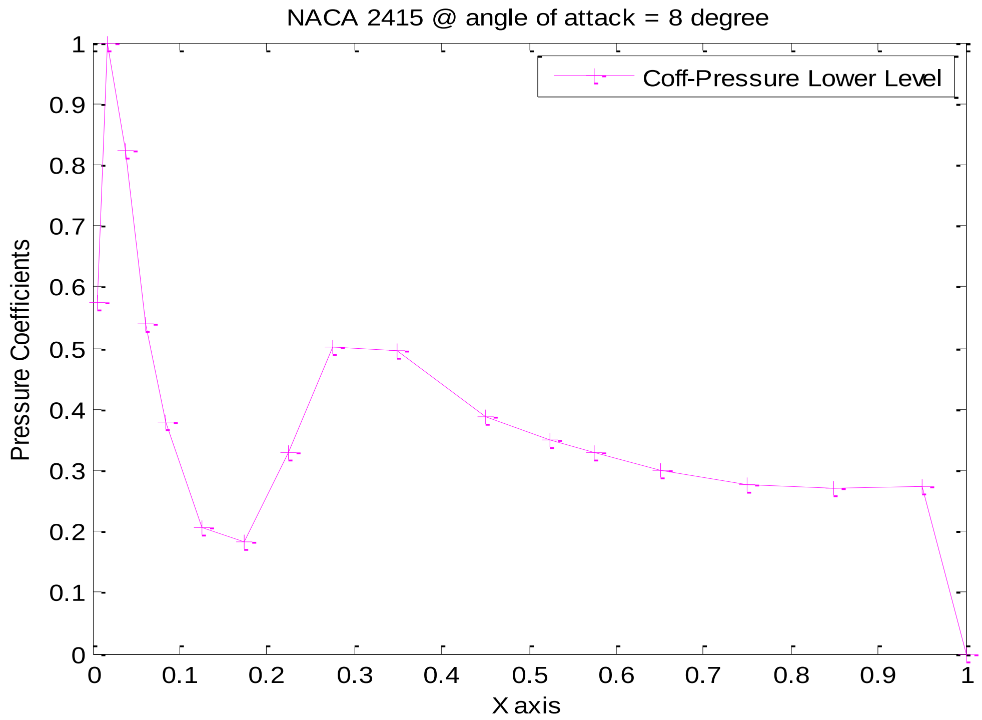
15 - The maximum thickness is 0.15c. (third and fourth digits)

An unusual curved surface form causes the air to move faster relative to the opposite side with respect to the position of the wing. This causes the difference in velocity of air moving both in contact and around the boundary layer. This difference in speed results in a difference in pressure between the top and the bottom of the wing which exerts a net force on the wing and depending upon the relative position of the wind with respect to flight path the net force can be upward or downward.

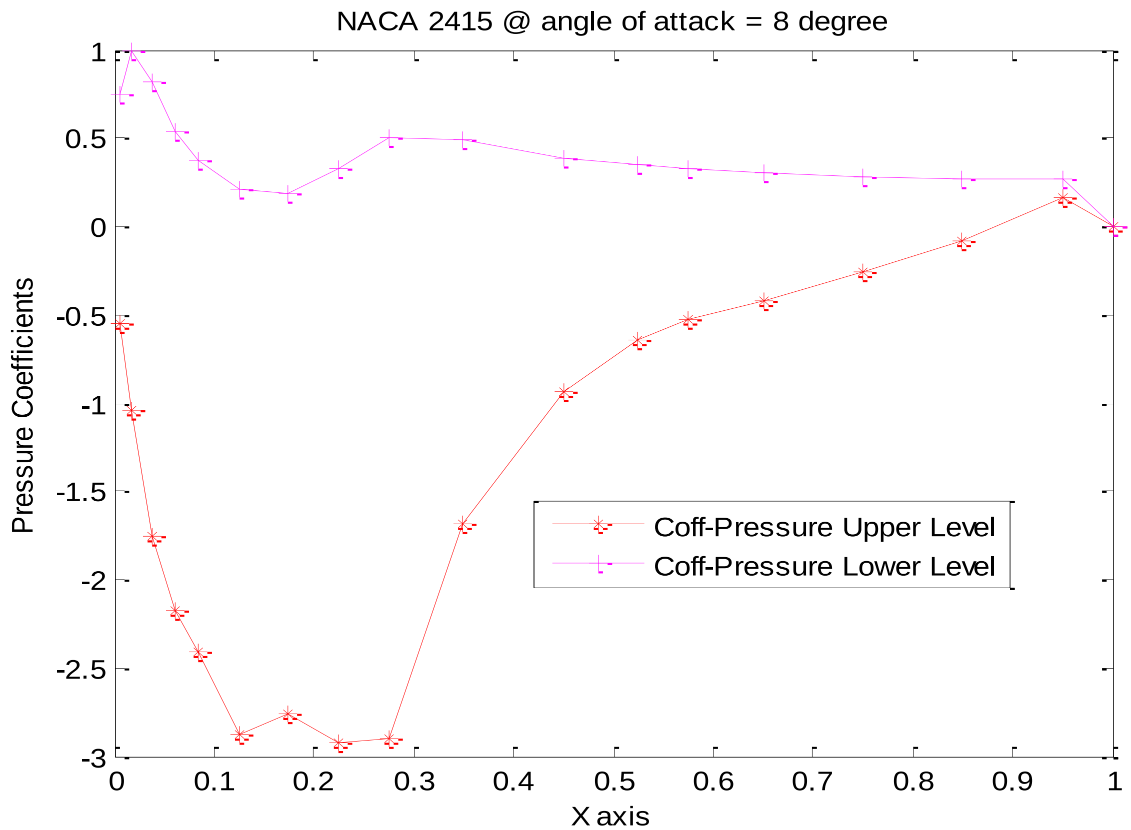
2) Pressure Distribution on the airfoil



Graph 1.0 The plot of pressure coefficient (C_p) on the upper level of the airfoil NACA 2415 against (X/c)



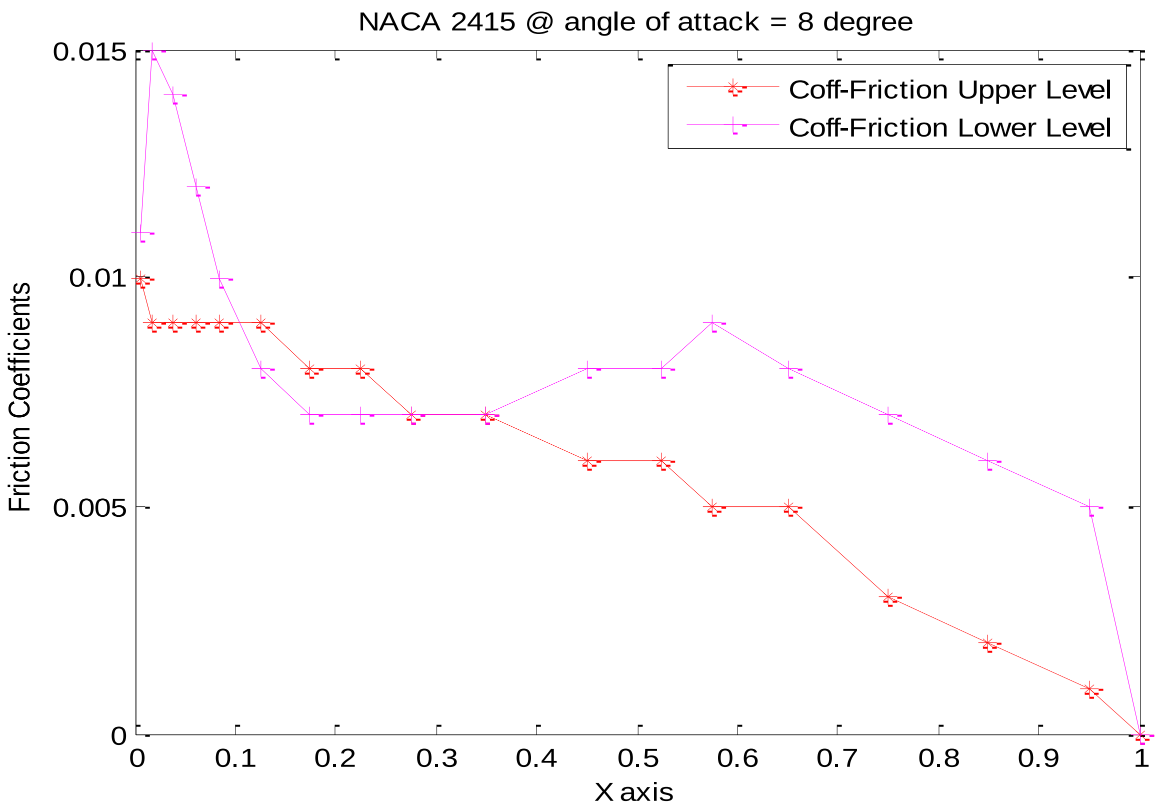
Graph 2.0 The plot of pressure coefficient (C_p) on the lower level of the airfoil NACA 2415 against (X/c)



Graph 3.0 The plot of pressure coefficient (C_p) on the Upper-lower level of the airfoil NACA 2415 against (X/c)

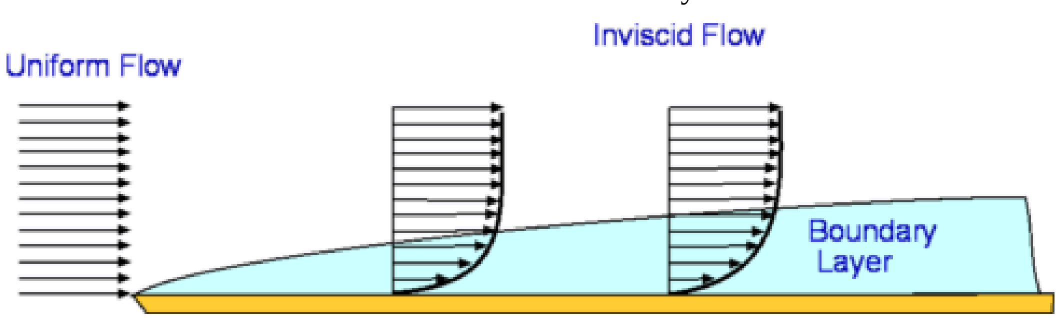
From the Graph 3.0 we can see the pressure distribution over the airfoil is not symmetric with valid the theoretical prediction the asymmetric geometry of the air body doesn't produce symmetrical distributed pressure over and below the surface and hence the net force act at different location creating the pitching moment. And also as the airfoil was subjected at 8 degree of angle of attack during the test, the corresponding data represent the high pressure under the surface than that of upper surface hence the lift coefficient is high.

3) Skin Friction over the airfoil



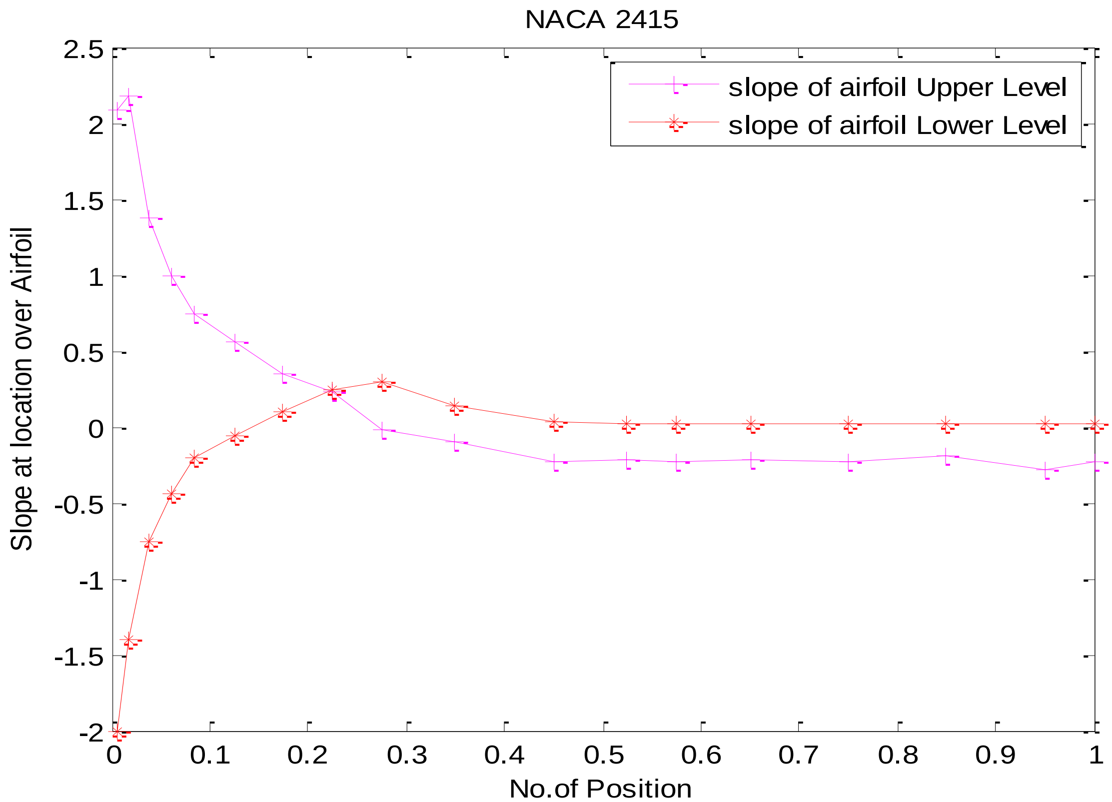
Graph 4.0 The plot of friction coefficient (C_f) on the Upper-lower level of the airfoil NACA 2415 against (X/c)

There are several sources of drag. One of them is skin friction, that is, the air stick to the surface of airfoil due to friction air and the body surface.



For a streamline body like airfoils, skin friction is the primary component of the drag, and pressure drag is relatively small. The skin friction is caused by fluid viscosity and roughness of the body surface as well as the Reynolds Number.

4) The slope dY/dX at each point location over the airfoil



Graph 5.0 The plot of slope (dy/dx) on the Upper-lower level of the airfoil NACA 2415 against (X/c)

The Graph 5.0 show how the slope of the airfoil changes at each location of the airfoil as the position along the surface change. The slope also gives the idea of non uniformity of the geometry of the airfoil.

5) Calculate the contributions of pressure and friction to the drag:

Friction drag is proportional to viscosity (roughly, the “stickiness” of the fluid). Fortunately, air has a rather low viscosity, so in most situations friction drag is small compared to pressure drag. In contrast, pressure drag depends on the mass density (not viscosity) of the air.

Friction drag and pressure drag both create a force in proportion to the area involved, and to the square of the airspeed. Part of the pressure drag that a wing produces depends on the amount of lift it is producing. This part of the drag is called *induced drag*. The rest of the drag — everything except induced drag — is called *parasite drag*.

Categories of Drag © http://www.av8n.com/how/htm/4forces.html

$$C_{D_p} = C_{n_p} * sin\alpha + C_{a_p} cos\alpha \ and \ C_{D_f} = C_{n_f} * sin\alpha + C_{a_f} cos\alpha$$

Where,

$$C_{n_P} = \frac{1}{c}\left[\int_0^1 \left(C_{p_l} - C_{p_u}\right) dx\right] \text{ and } C_{a_P} = \frac{1}{c}\left[\int_0^1 \left(C_{p_u} * \frac{dY_u}{dX} - C_{p_l} * \frac{dY_l}{dX}\right) dx\right]$$

$$C_{n_f} = \frac{1}{c}\left[\int_0^1 \left(C_{f_u} * \frac{dY_u}{dX} + C_{f_l} * \frac{dY_l}{dX}\right) dx\right] \text{ and } C_{a_f} = \frac{1}{c}\left[\int_0^1 \left(C_{f_l} + C_{f_u}\right) dx\right]$$

6) Calculate the lift, drag and moment coefficients:

We know,

$$C_L = \frac{L}{q_\infty * S}, \quad C_D = \frac{D}{q_\infty * S}, \quad C_n = \frac{N}{q_\infty * S}, \quad C_a = \frac{A}{q_\infty * S}$$

and

$$L = Ncos\alpha - Asin\alpha$$

$$D = Nsin\alpha + Acos\alpha$$

Dividing by $\frac{1}{q_\infty * S}$

$$\frac{L}{q_\infty * S} = \frac{N}{q_\infty * S} cos\alpha - \frac{A}{q_\infty * S} sin\alpha$$

$$C_l = C_n * cos\alpha - C_a sin\alpha$$

$$\frac{D}{q_\infty * S} = \frac{N}{q_\infty * S} sin\alpha + \frac{A}{q_\infty * S} cos\alpha$$

$$C_D = C_n * sin\alpha + C_a cos\alpha$$

Where,

$$C_n = \frac{1}{c}\left[\int_0^1 \left(C_{p_l} - C_{p_u}\right) dx + \int_0^1 \left(C_{f_u} * \frac{dY_u}{dX} + C_{f_l} * \frac{dY_l}{dX}\right) dx\right]$$

$$C_a = \frac{1}{c}\left[\int_0^1 \left(C_{f_l} + C_{f_u}\right) dx + \int_0^1 \left(C_{p_u} * \frac{dY_u}{dX} - C_{p_l} * \frac{dY_l}{dX}\right) dx\right]$$

$$C_{m_{LE}} = \frac{1}{c^2}\left[\int_0^1 \left(C_{p_l} - C_{p_u}\right) * X * dx - \int_0^1 \left(C_{f_u} * \frac{dY_u}{dX} + C_{f_l} * \frac{dY_l}{dX}\right) * X * dx\right] +$$
$$\frac{1}{c^2}\left[\int_0^1 \left(C_{p_u} * \frac{dY_u}{dX} + C_{f_u}\right) * Y_u * dx + \int_0^1 \left(-C_{p_l} * \frac{dY_l}{dX} + C_{f_l}\right) * Y_l * dx\right]$$

7) MatLab results

Parameters	**Value**
Drag Due to Friction Drag Due to Pressure	0.0128 -0.0553
FIRST METHOD: TRAPEZIODAL METHOD	
The coefficient of LIFT is: The coefficient of Drag is: The coefficient of moment about leading edge is:	1.5136 -0.0425 0.4239
SECOND METHOD: SIMPSON RULE	
The coefficient of LIFT is: The coefficient of Drag is: The coefficient of moment about leading edge is:	1.3977 -0.0287 0.4054
Reference External Source (Re=3*10^6, Ma<0.17)	
The coefficient of LIFT is: The coefficient of Drag is: The coefficient of moment about leading edge is:	1.00 0.012 -0.4054

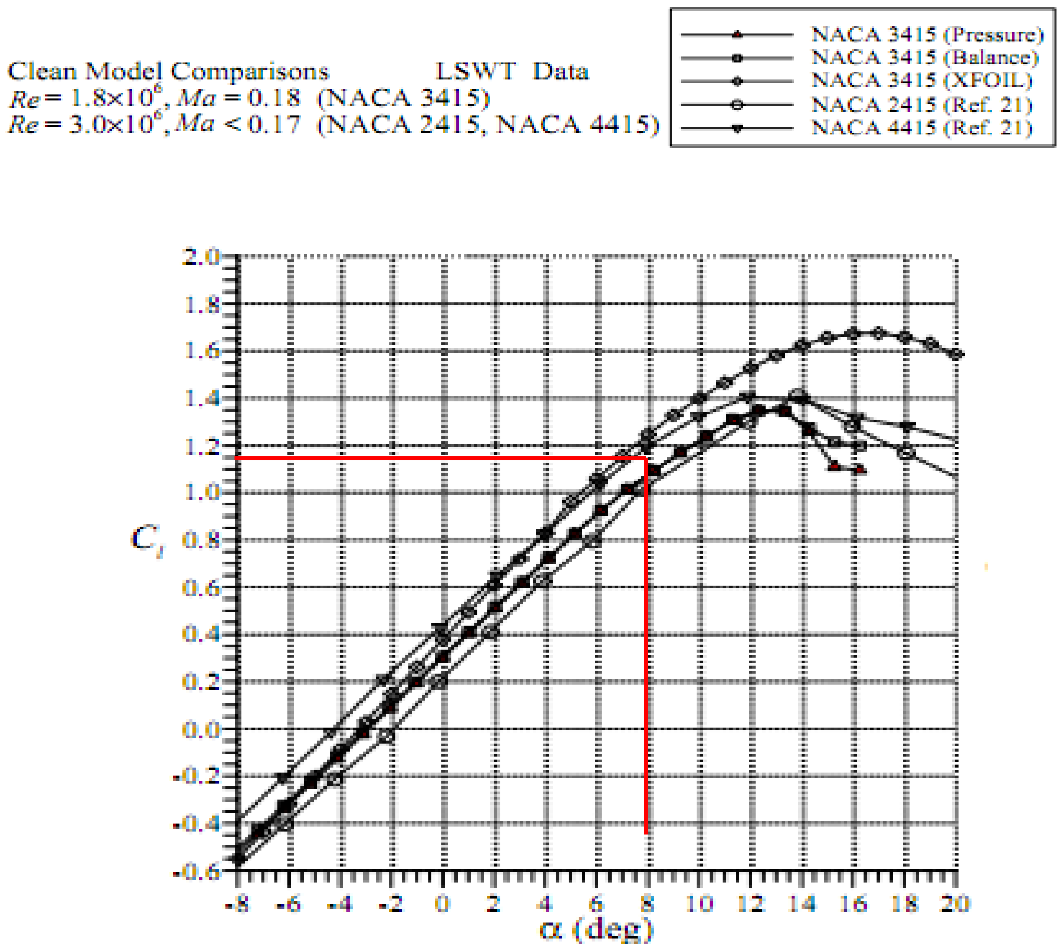
Table 1.0 Numerical Results

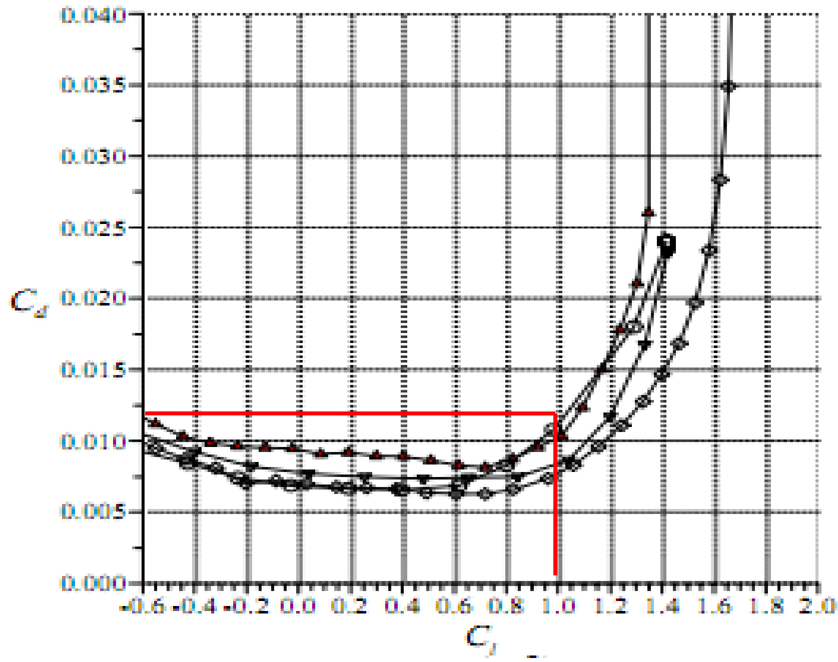
Comments:

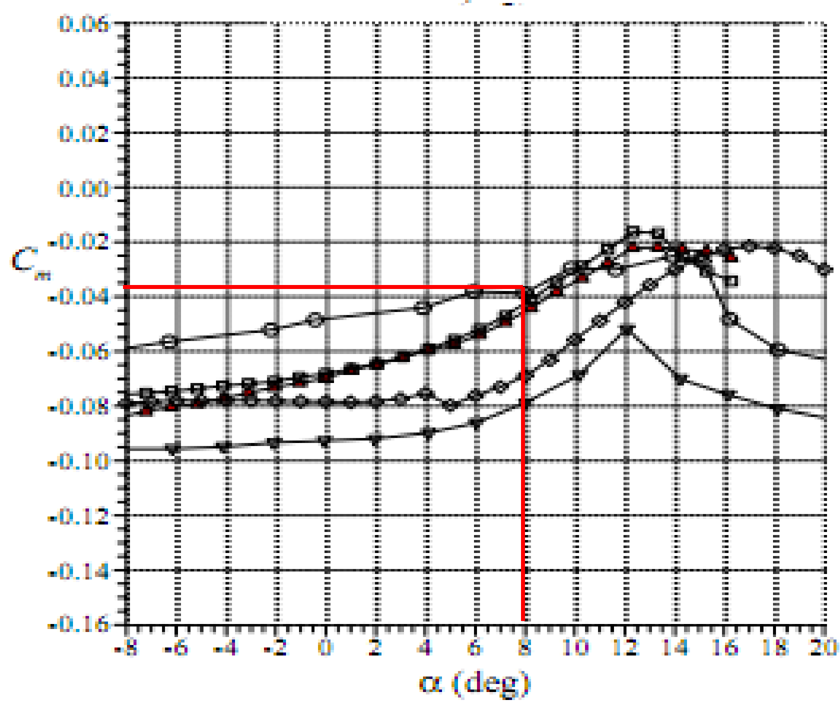
First the drag was calculated each time independent of friction in first case and independent of pressure in second case. The results was relevant with respect to the drag induce due to friction however the drag due to pressure was obtained to be negative which not coherent with the theoretical prediction, that is drag can't act as the thrust to the system. Therefore it can be concluded with the pressure coefficient data obtained during experiment is wrong or possess error.

As from the result obtained above for drag, it was obvious that the further analysis will certainly have error. Using two different numerical method trapezoidal and Simpson Rule method for numerical integration, the result was obtained and compared with external source. The both the numerical results were obtained in close proximity. However it was also observed the SIMPSON RULE yield 50% reduction in Drag Coefficient. Since the Reynolds number in the experiment was conducted is unknown, therefore a reference was taken at Re=3*10^6 and the obtained results were compared. Though the value of the lift coefficient value was close to the one in reference source that it 1.0 which was approximated to be around 1.51 and 1.39 by numerical integration methods (i.e. Trapezoidal and Simpson Rule) respectively. However, the drag coefficient and moment coefficient was completely against the agreement with huge factor hence was incomprehensive. This result could have been yield due to the data tabulation error and poor experimental technique during experimentation. Some error is always attributed to the truncation error in numerical integration however the results for this data are beyond the allowable limits and hence can be concluded to be wrong.

8) Appendix




0.040
0.035
0.030
0.025
C_d 0.020
0.015
0.010
0.005
0.000
-0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
C_l


0.06
0.04
0.02
0.00
C_m -0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20
α (deg)

```
close all
clear all
clc

% Wind Tunnel measurments of Pressure and Skin frinction around NACA 2415

Angle_of_attack = 8;     % degree
Angle_of_attack_rad=Angle_of_attack*pi/180;

data=load('wind_tunnel.txt');

% Load X-axis
X_axis=data(:,2);

% Load Y-axis
Y_axis=data(:,3);

% Load Lower Pressure Coefficient
C_P_L=data(1:18,4);
for i=1:1:18
    C_p_L(i,1)=C_P_L(19-i,1);
end

% Load Upper X-position, Y-position, Pressure Coff. and friction Coff.
X_c_U=X_axis(19:36,:);
Y_c_U=Y_axis(19:36,:);
C_P_U=data(19:36,4);
C_F_U=data(19:36,5).*10^-3;


% Load Lower X-position, Y-position, Pressure Coff. and friction Coff.
X_C_L=X_axis(1:18,:);
Y_C_L=Y_axis(1:18,:);
C_p_L=data(1:18,4);
C_f_L=data(1:18,5).*10^-3;

%  Changing the value.
for i=1:1:18
    C_P_L(i,1)= C_p_L(19-i,1);
    C_F_L(i,1)= C_f_L(19-i,1);
    X_c_L(i,1)= X_C_L(19-i,1);
    Y_c_L(i,1)= Y_C_L(19-i,1);
end

% Calculate the slope for upper
dydx_U(1,1)=Y_c_U(1,1)/X_c_U(1,1);
for i=2:1:18
    dydx_U(i,1)=(Y_c_U(i,1)-Y_c_U(i-1,1))/(X_c_U(i,1)-X_c_U(i-1,1));
end

% Calculate the slope for Lower
dydx_L(1,1)=Y_c_L(1,1)/X_c_L(1,1);
for i=2:1:18
```

```
    dydx_L(i,1)=(Y_c_L(i,1)-Y_c_L(i-1,1))/(X_c_L(i,1)-X_c_L(i-1,1));
end

% Calculate the differential element
dx_c(1,1)=0;
for i=2:1:18
    dx_c(i,1)=X_c_U(i)-X_c_U(i-1);
end


% Normal components
C_n_p=(C_P_L-C_P_U);                     % Pressure component
C_n_f=C_F_U.*dydx_U+C_F_L.*dydx_L;      % Friction component

% Axial components
C_a_p=C_P_U.*dydx_U-C_P_L.*dydx_L;      % Pressure component
C_a_f=(C_F_L+C_F_U);                     % Friction

% Momentum components
C_m_P_ul=(C_P_L-C_P_U).*X_c_U;
C_m_f_ul=(C_F_U.*dydx_U+C_F_L.*dydx_L).*X_c_U;
C_m_PF_U=(C_P_U.*dydx_U+C_F_U).*Y_c_U;
C_m_PF_L=(-C_P_L.*dydx_L+C_F_L).*Y_c_L;


% Drag Due to Pressure and Friction
C_n_pp=0;C_a_pp=0;C_n_ff=0;C_a_ff=0;

for i=1:1:17
    C_n_pp=C_n_pp+(X_c_U(i+1)-X_c_U(i))*(C_n_p(i)+C_n_p(i+1))/2;

    C_a_pp=C_a_pp+(X_c_U(i+1)-X_c_U(i))*(C_a_p(i)+C_a_p(i+1))/2;

    C_n_ff=C_n_ff+(X_c_U(i+1)-X_c_U(i))*(C_n_f(i)+C_n_f(i+1))/2;

    C_a_ff=C_a_ff+(X_c_U(i+1)-X_c_U(i))*(C_a_f(i)+C_a_f(i+1))/2;
end
C_D_P=C_n_pp*sin(Angle_of_attack_rad)+C_a_pp*cos(Angle_of_attack_rad);
C_D_F=C_n_ff*sin(Angle_of_attack_rad)+C_a_ff*cos(Angle_of_attack_rad);

% First Numerical Method
C_n_1=0;C_a_1=0;C_m_1=0;

for i=1:1:17
    C_n_1=C_n_1+(X_c_U(i+1)-X_c_U(i))*(C_n_p(i)+C_n_p(i+1))/2....
        +(X_c_U(i+1)-X_c_U(i))*(C_n_f(i)+C_n_f(i+1))/2;

    C_a_1=C_a_1+(X_c_U(i+1)-X_c_U(i))*(C_a_p(i)+C_a_p(i+1))/2....
        +(X_c_U(i+1)-X_c_U(i))*(C_a_f(i)+C_a_f(i+1))/2;

    C_m_1=C_m_1+(X_c_U(i+1)-X_c_U(i))*(C_m_P_ul(i)+C_m_P_ul(i+1))/2....
        +(X_c_U(i+1)-X_c_U(i))*(C_m_f_ul(i)+C_m_f_ul(i+1))/2....
        +(X_c_U(i+1)-X_c_U(i))*(C_m_PF_U(i)+C_m_PF_U(i+1))/2....
        +(X_c_U(i+1)-X_c_U(i))*(C_m_PF_L(i)+C_m_PF_L(i+1))/2;
```

```
end

C_L_1=C_n_1*cos(Angle_of_attack_rad)-C_a_1*sin(Angle_of_attack_rad);
C_D_1=C_n_1*sin(Angle_of_attack_rad)+C_a_1*cos(Angle_of_attack_rad);

% Second Numerical Method
C_n_2=0;C_a_2=0;C_m_2=0;

for i=1:1:16
    C_n_2=C_n_2+(X_c_U(i+1)-
X_c_U(i))/6*(C_n_p(i)+4*C_n_p(i+1)+C_n_p(i+2))....
        +(X_c_U(i+1)-X_c_U(i))/6*(C_n_f(i)+4*C_n_f(i+1)+C_n_f(i+2));

    C_a_2=C_a_2+(X_c_U(i+1)-
X_c_U(i))/6*(C_a_p(i)+4*C_a_p(i+1)+C_a_p(i+2))....
        +(X_c_U(i+1)-X_c_U(i))/6*(C_a_f(i)+4*C_a_f(i+1)+C_a_f(i+2));

    C_m_2=C_m_2+(X_c_U(i+1)-
X_c_U(i))/6*(C_m_P_ul(i)+4*C_m_P_ul(i+1)+C_m_P_ul(i+2))....
        +(X_c_U(i+1)-
X_c_U(i))/6*(C_m_f_ul(i)+4*C_m_f_ul(i+1)+C_m_f_ul(i+2))....
        +(X_c_U(i+1)-
X_c_U(i))/6*(C_m_PF_U(i)+4*C_m_PF_U(i+1)+C_m_PF_U(i+2))....
        +(X_c_U(i+1)-X_c_U(i))/6*(C_m_PF_L(i)+4*C_m_PF_L(i+1)+C_m_PF_L(i+2));
end

C_L_2=C_n_2*cos(Angle_of_attack_rad)-C_a_2*sin(Angle_of_attack_rad);
C_D_2=C_n_2*sin(Angle_of_attack_rad)+C_a_2*cos(Angle_of_attack_rad);


disp(' Drag Due to Pressure')
disp(C_D_P)
disp(' Drag Due to Friction')
disp(C_D_F)


disp('FIRST METHOD: TRAPEZIODAL METHOD')
disp('The coefficient of LIFT is: ')
disp(C_L_1)
disp('The coefficient of drag is: ')
disp(C_D_1)
disp('The coefficient of moment about leading edge is: ')
disp(C_m_1)


disp('SECOND METHOD: SIMPSON RULE')
disp('The coefficient of LIFT is: ')
disp(C_L_2)
disp('The coefficient of drag is: ')
disp(C_D_2)
disp('The coefficient of moment about leading edge is: ')
disp(C_m_2)

figure(1)
```

```
plot(X_axis,Y_axis,'-ok')
xlabel('X axis')
ylabel('Y axis')
title('NACA 2415')

figure(2)
plot(X_c_U,C_P_U,'-*r')
xlabel('X axis')
ylabel('Pressure Coefficients')
title('NACA 2415 @ angle of attack = 8 degree')
legend('Coff-Pressure Upper Level')

figure(3)
plot(X_c_L,C_P_L,'-+m')
xlabel('X axis')
ylabel('Pressure Coefficients')
title('NACA 2415 @ angle of attack = 8 degree')
legend('Coff-Pressure Lower Level')

figure(4)
plot(X_c_U,C_P_U,'-*r',X_c_L,C_P_L,'-+m')
xlabel('X axis')
ylabel('Pressure Coefficients')
title('NACA 2415 @ angle of attack = 8 degree')
legend('Coff-Pressure Upper Level','Coff-Pressure Lower Level')

figure(5)
plot(X_c_U,C_F_U,'-*r',X_c_L,C_F_L,'-+m')
xlabel('X axis')
ylabel('Friction Coefficients ')
title('NACA 2415 @ angle of attack = 8 degree')
legend('Coff-Friction Upper Level','Coff-Friction Lower Level')

figure(6)
plot(X_c_U,dydx_U,'-+m')
hold on
plot(X_c_L,dydx_L,'-*r')
xlabel('No.of Position')
ylabel('Slope at location over Airfoil')
title('NACA 2415')
legend('slope of airfoil Upper Level','slope of airfoil Lower Level')
```

9) Reference

- http://www.tc.faa.gov/its/worldpac/techrpt/ar03-64.pdf
- Anderson, John D. "Fundamentals of Aerodynamics" McGraw Hill. 2001: 3rd edition.