1. Description of Tests

The selected 3D-printed airfoil (NACA-0012) was measured to have a chord length of 140mm and a span of 200mm. A strain gage-based load cells was mounted behind the rod that holds the airfoil to measure the forces and moment. The angle of attack of the airfoil was calibrated by using a digital level gauge to measure the initial angle which is positive 3°. Data was taken from an angle of attack of 18° to -12° with an increment steps of 1° pausing for a few seconds at each angle to data collection. The wind speed knob on the VI was used to adjust the wind speed and air speed was measured using a hand-held hot wire thermo-anemometer inserted in the wind tunnel that allows simultaneous measurement of temperature and speed. The desired air speed corresponds to Reynolds number of 50,000 was calculated using equation (1) which matches the published dataset for the selected airfoil. Five trials were collected and during each trial, the wing started at the extreme positive angle of attack and ended at the negative extreme. For the second part, a smartphone camera was used to record slow motion at 240 fps. The smartphone was clamped to prevent any movement. The wind tunnel was operated at lower speed to get a better visualization and the angle of attack used are at 5^o until 20^o. The video was cropped and break into frames and further analysis was made to visualize the changes in streamline patterns from different angle of attack

2. Data Analysis

The Reynolds number was calculated using the following equation:

$$Re = \frac{\rho V^2 L}{\mu} \quad (1)$$

where ρ is air density, V is the velocity, L is the chord length and μ is the air viscosity. Throughout the experiment, the air temperature was taken by using the anemometer while the pressure and humidity was taken from the room monitor. The forces and moments data was post-processed using a moving average to filter out noise from the sensor readings in the plots (Figure 2). After that, the coefficient of lift, drag and moment was obtained using the following equations:

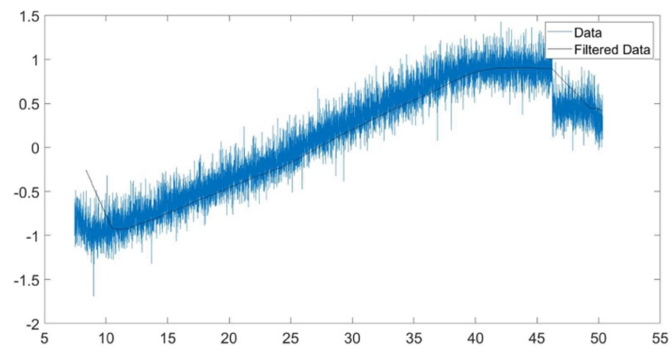

Figure 2: Pre-filtered data of lift coefficient against alpha

$$Cl = \frac{2F_l}{\rho A V^2} \quad (2) \qquad Cd = \frac{2F_d}{\rho A V^2} \quad (3) \qquad Cm = \frac{2M}{\rho V^2 A c} \quad (4)$$

where F_l, F_d and M are lift force, drag force and moment respectively, A is the reference area which is chord length c times blade length L. When the data was compared to the published data taken from airfoiltools.com [1] the absolute magnitude of the coefficients for the tested data were scaled off compared to the published data, indicating that the setup was not entirely valid due to certain errors. As a result, the maximum and the minimum value of the obtained was fitted to match the reference.

For the visualization part, several angle was taken taken to measure the frequency of vortex shedding that can be related to Strouhal number. The stagnation point, upper separation, size of downstream wake and speed of vortex core were compared at 5^o and 7^o where the visualization is better. The equation for Strouhal number is:

$$St = \frac{ft}{V} \quad (5)$$

where f is frequency of the vortex shedding, t is the airfoil thickness and V is the air speed

2.1 Lift Coefficient and Drag Coefficient vs Angle of Attack

The coefficient of lift and drag are dimensionless quantity based on equation (2) and (3) which are function of angles and they are really useful to compare the properties of airfoils. The coefficient of lift is negative for the negative angle and positive for the positive angle (Figure 2.1.1). The positive value means that force is lifting it while negative means that the force is acting downwards. Meanwhile, the coefficient of drag is always positive for both maximum and minimum angle meaning that the surface area of the wing normal to the direction of airflow is maximized (Figure 2.1.2). The trend of lift and drag coefficients are quite similar compare to the published airfoil. Since the collected data was sampled for a much higher range of angle of attack, the data for lift and drag extends outwards.

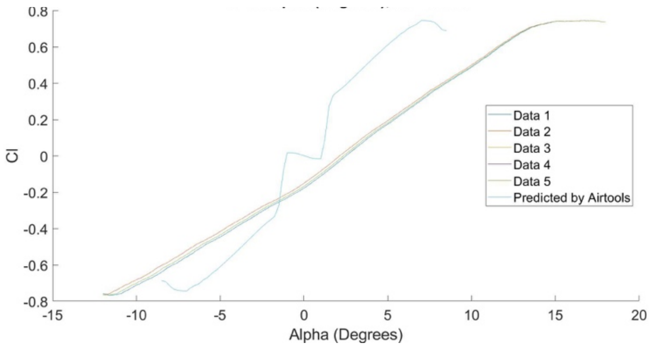

Figure 2.1.1: Coefficient of lift vs alpha for Re=50,000

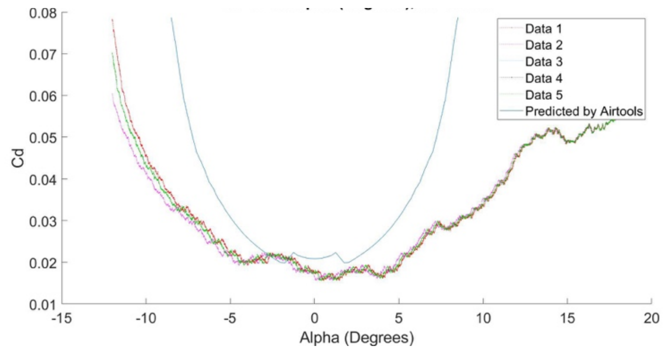

Figure 2.1.1: Coefficient of drag vs alpha for Re=50,000

2.2 Lift Coefficient vs Drag Coefficient

To visualize the range of lift values at a given drag, the Cl vs Cd was plotted to show that an increase in lift does not result in increase in drag over a range of angle of attack (figure). For a constant coefficient of drag, there are wide values of lift possible. It can be seen that the shape of the plots follows the expected data after the filtering and scaling process. The data for all the runs overlapped because the ratio of Cl and Cd is a constant since the drag and lift force is a component vector of each other.

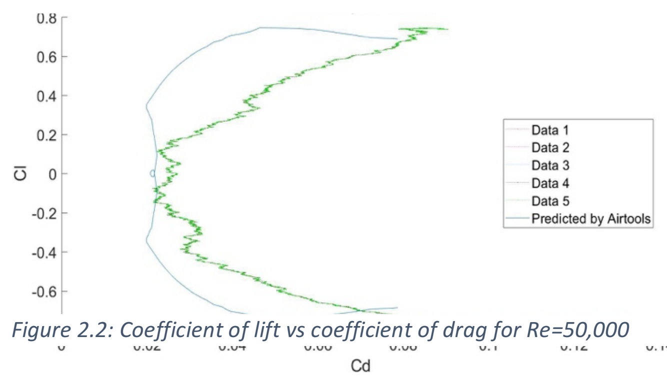

Figure 2.2: Coefficient of lift vs coefficient of drag for Re=50,000

2.3 Lift/Drag Coefficient vs Angle of Attack

The efficiency of an airfoil in creating lift with minimal drag can be visualize with Cl/Cd vs angle of attack plot (figure). The optimal angle of attack to obtain the maximum lift is approximately 8^{o} meanwhile to obtain optimum negative lift is about -5^{o}. The shape of the plots is quite similar to the published data. However, the magnitude of optimum positive and negative Cl is lower compared to the referenced data by a few degrees which might be caused by certain errors.

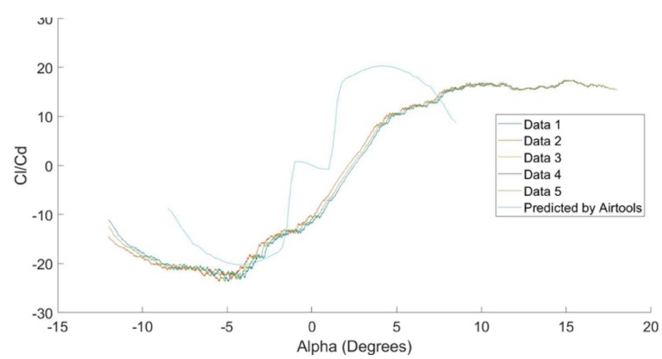

Figure 2.3: Coefficient of lift/drag vs alpha for Re= 50,000

2.4 Moment Coefficient vs Angle of Attack

The moment coefficient is also a dimensionless quantity based on equation (4) which is a function of moment that changes with angle of attack. Since the data collected was sampled for a much higher range of angle of attack, the data for lift and drag extends outwards (figure).

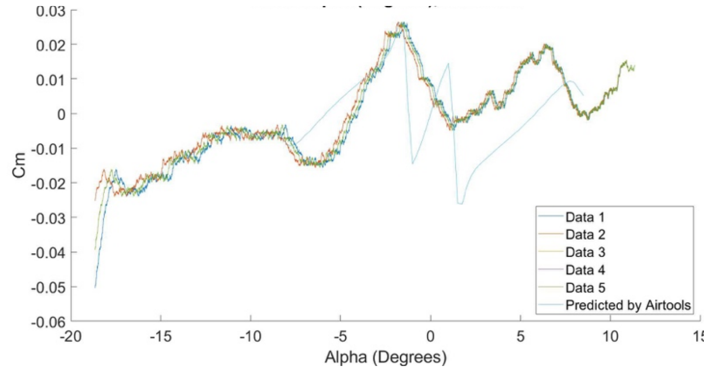

Figure 2.4: Coefficient of moment vs alpha for Re= 50,000

2.5 Visualize Changes

From the two angle of attack which is 5^o and 7^o, the characteristics of air flow at 0.8 m/s can be observed. Firstly, the position of stagnation point is lower on the airfoil leading for higher angle of attack. From the image, only the upper separation point can be observed since the lower separation point is covered by the airfoil. It can be observed, the bigger the angle of attack, the earlier the separation point. Moreover, the growth of the downstream wake is larger for the 7^o compared to the 5^o. From observation, is observed that the speed of the vortex core moves slower relative to the far-air speed as the angle of attack increased. Based on (Table 1), the frequency of vortex shedding decreases as the angle of attack increases. The Strouhal number was calculated based on the frequency of vortex shedding using equation (5).

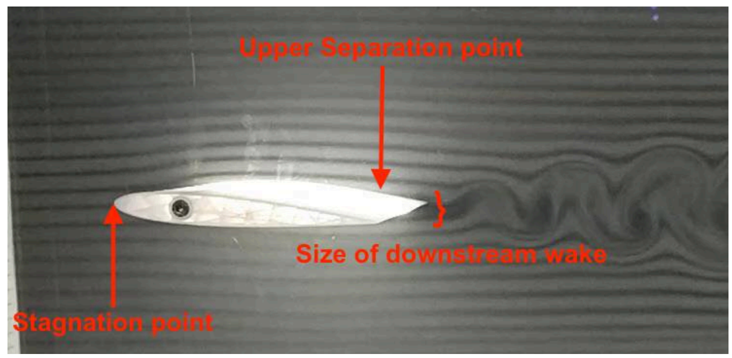

Figure 2.5.1: 33^{rd} frame for alpha= 5^o at 0.8m/s

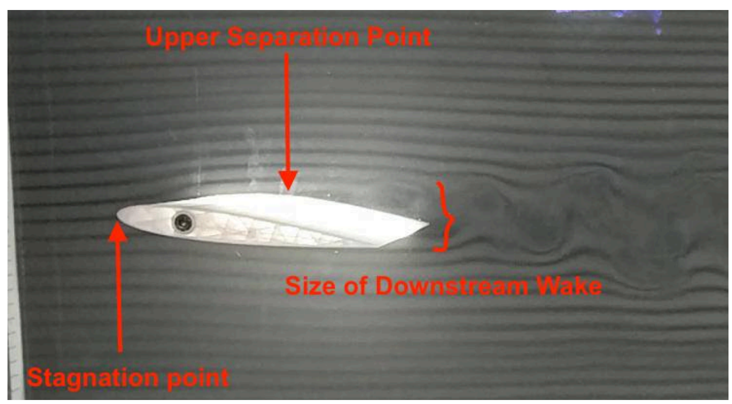

Figure 2.5.2: 33^{rd} frame for alpha= 7^o at 0.8m/s

3. Discussion

Overall, it was discovered that the tested airfoil (NACA-0012) followed the expected published trends at 50,000 Reynolds number with some discrepancy between the reference and tested data especially in the slight underestimation of lift and drag coefficient. These can be observed clearly in the Cl/Cd plots. The magnitude error could be caused by the surface roughness of the airfoil due to limitation of 3D printers. Moreover, load cell reading, anemometer measurement, and angular measurement noise are also the sources of uncertainty associated with the experiment. These sources have been accounted through calibration, scaling and filtering. The uniformity of the airflow in the wind tunnel was not guaranteed due to the oscillations in the velocity since the the desired velocity depends on the air properties based on (equation 1). During the experiment we noted that the temperature increases from 20.4^oC to 21.4^oC that might be caused by the wind tunnel heating up varying the density and viscosity of the air that was obtained from the website [2][3]. As a result, the exact desired Reynolds number changes throughout the experiment. Additionally, there are also potential outside disturbance that affected the flow characteristics.

Angle of Attack	Frequency of vortex shedding	Strouhal Number
5^o	11.86/s	0.249
7^o	8.78/s	0.184
10^o	7.23/s	0.152
15^o	5.71/s	0.120
20^o	4.31/s	0.091

Table 1: Frequency of vortex shedding and their respecting Strouhal Number at different angle of attack

Reference:

[1] LOCKHEED C-5A BL0 AIRFOIL (c5a-il). http://airfoiltools.com/airfoil/naca4digit. Accessed: March 01, 2019.

[2] Dominik Czernia. https://www.omnicalculator.com/physics/air-density. Accessed: March 01, 2019

[3] Air - Dynamic and Kinematic Viscosity. https://www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601.html. Accessed: March 01, 2019

Contents


```
clc
clear all
load('data.mat') % has data imported from CSV
load('NACA.mat') % has theoretical data for airfoil
set(0,'defaultAxesFontSize',18)
```

```
lift1=Untitled1.FDN; lift2=Untitled2.FDN; lift3=Untitled3.FDN; lift4=Untitled4.FDN;
lift5=Untitled5.FDN;
drag1=Untitled1.FLN; drag2=Untitled2.FLN; drag3=Untitled3.FLN; drag4=Untitled4.FLN;
drag5=Untitled5.FLN;
fmom1=Untitled1.FMNm; fmom2=Untitled2.FMNm; fmom3=Untitled3.FMNm; fmom4=Untitled4.FMNm;
fmom5=Untitled5.FMNm;
time1=linspace(0,120,length(Untitled1.FMNm));time2=linspace(0,120,length(Untitled2.FMNm));
time3=linspace(0,120,length(Untitled3.FMNm));time4=linspace(0,120,length(Untitled4.FMNm));
time5=linspace(0,120,length(Untitled5.FMNm));
Nalpha=M(:,1);NCl=M(:,2);NCd=M(:,3);NCm=M(:,5);
```

1

```
clear filterD1 filterL1 filterfmom1
b = 1/1000*ones(1,1000);
a=1;
filterD1= filter(b,a,drag1(2445:16509)); filterL1= filter(b,a,lift1(2445:16509));
filterfmom1= filter(b,a,fmom1(2445:16509));
filterD1= -1*filterD1;
filterL1= -1*filterL1;
[pks1,locs1]=findpeaks(filterD1,'MinPeakDistance',8000);
D1=filterD1(locs1(1):locs1(2));
L1=filterL1(locs1(1):locs1(2));
Fm1=filterfmom1(locs1(1):locs1(2));
angle1=linspace(-15+3,15+3,length(D1));  %off by 3 degree
```

2

```
clear filterD2 filterL2 filterfmom2
filterD2= filter(b,a,drag2(2710:17170));
filterL2= filter(b,a,lift2(2710:17170));
filterfmom2= filter(b,a,fmom2(2710:17170));
filterD2= -1*filterD2;
filterL2= -1*filterL2;
[pks2,locs2]=findpeaks(filterD2,'MinPeakDistance',8000);
D2=filterD2(locs2(1):locs2(2));
L2=filterL2(locs2(1):locs2(2));
Fm2=filterfmom2(locs2(1):locs2(2));
angle2=linspace(-15+3,15+3,length(D2));
```

3

```
clear filterD3 filterL3 filterfmom3
filterD3= filter(b,a,drag3(650+1900:16290));
filterL3= filter(b,a,lift3(650+1900:16290));
filterfmom3= filter(b,a,fmom3(650+1900:16290));
filterD3= -1*filterD3;
filterL3= -1*filterL3;
[pks3,locs3]=findpeaks(filterD3,'MinPeakDistance',8000);
D3=filterD3(locs3(1):locs3(2));
L3=filterL3(locs3(1):locs3(2));
Fm3=filterfmom3(locs3(1):locs3(2));
angle3=linspace(-15+3,15+3,length(D3));
```

4

```
clear filterD4 filterL4 filterfmom4
filterD4= filter(b,a,drag4(650+1900:16290));
filterL4= filter(b,a,lift4(650+1900:16290));
filtermom4= filter(b,a,fmom4(650+1900:16290));
filterD4= -1*filterD4;filterL4= -1*filterL4;
[pks4,locs4]=findpeaks(filterD4,'MinPeakDistance',8000);
D4=filterD4(locs4(1):locs4(2));L4=filterL4(locs4(1):locs4(2));
Fm4=filtermom4(locs4(1):locs4(2));angle4=linspace(-15+3,15+3,length(D4));
```

5

```
clear filterD5 filterL5 filterfmom5
filterD5= filter(b,a,drag5(650+1900:16290));
filterL5= filter(b,a,lift5(650+1900:16290));
filtermom5= filter(b,a,fmom5(650+1900:16290));
filterD5= -1*filterD5;filterL5= -1*filterL5;
[pks5,locs5]=findpeaks(filterD5,'MinPeakDistance',8000);
D5=filterD5(locs5(1):locs5(2));L5=filterL5(locs5(1):locs5(2));
Fm5=filtermom5(locs5(1):locs5(2));angle5=linspace(-15+3,15+3,length(D5));
```

```
CF= 2/(1.245*(5.9^2)*0.2*0.14);
CM= 2/(1.245*(5.9^2)*0.2*(0.14^2));
Re= (1.245*5.9*0.14)/(18.15e-6);
% reynold number approximately 50 000

figure
hold on
plot(angle1,D1*CF*0.57,':r*','MarkerSize',0.2);plot(angle2,D2*CF*0.57,':mo','MarkerSize',0
.2);plot(angle3,D3*CF*0.57,':cs','MarkerSize',0.2);plot(angle4,D4*CF*0.57,':k+','MarkerSiz
e',0.2);plot(angle5,D5*CF*0.57,':gp','MarkerSize',0.2);
fig=plot(Nalpha,NCd);
hold off
title('Cd vs vs Alpha (Degrees), Re=50000')
xlabel('Alpha (Degrees)')
ylabel('Cd')
legend('Data 1', 'Data 2', 'Data 3','Data 4', 'Data 5','Predicted by Airtools','location',
 'northeast')
%saveas(fig,'AlphavsCd.jpg')
```

```
figure
hold on
plot(angle1,L1*CF*0.4992);plot(angle2,L2*CF*0.4992);plot(angle3,L3*CF*0.4992);plot(angle4,
L4*CF*0.4992);plot(angle5,L5*CF*0.4992);
fig = plot(Nalpha,NCl);
hold off
title('Cl vs Alpha (Degrees), Re=50000')
xlabel('Alpha (Degrees)')
ylabel('Cl')
legend('Data 1', 'Data 2', 'Data 3','Data 4', 'Data 5','Predicted by Airtools','location',
 'east')
%saveas(fig,'AlphavsCl.jpg')
```

```
figure
hold on
plot(angle1,L1./D1);plot(angle2,L2./D2);plot(angle3,L3./D3);plot(angle4,L4./D4);plot(angle
5,L5./D5);
fig =plot(Nalpha,NCl./NCd);
hold off
title('Cl/Cd vs Alpha (Degrees), Re=50000')
xlabel('Alpha (Degrees)')
ylabel('Cl/Cd')
legend('Data 1', 'Data 2', 'Data 3','Data 4', 'Data 5','Predicted by Airtools','location',
 'east')
%saveas(fig,'AlphavsClCd.jpg')
```

```
figure
hold on
plot(D1*CF-0.006,L1*CF*0.4992,':r*','MarkerSize',0.1);plot(D2*CF-0.006,L2*CF*0.4992,':mo',
'MarkerSize',0.1);plot(D3*CF-0.006,L3*CF*0.4992,':cs','MarkerSize',0.1);plot(D4*CF-0.006,L
4*CF*0.4992,':k+','MarkerSize',0.1);plot(D5*CF-0.006,L5*CF*0.4992,':gp','MarkerSize',0.2);
fig= plot(NCd,NCl);
hold off
title('Cl vs Cd, Re=50000')
xlabel('Cd')
ylabel('Cl')
legend('Data 1', 'Data 2', 'Data 3','Data 4', 'Data 5','Predicted by Airtools','location',
 'east')
%saveas(fig,'CdvsCl.jpg')
```

```
figure
hold on
plot(angle1-6.65,Fm1*CM*1.214);plot(angle2-6.65,Fm2*CM*1.214);plot(angle3-6.65,Fm3*CM*1.21
4);plot(angle4-6.65,Fm4*CM*1.214);plot(angle5-6.65,Fm5*CM*1.214);
fig=plot(Nalpha,NCm);
hold off
title('Cm vs Alpha (Degrees), Re=50000')
xlabel('Alpha (Degrees)')
ylabel('Cm')
legend('Data 1', 'Data 2', 'Data 3','Data 4', 'Data 5','Predicted by Airtools','location',
 'southeast')
%saveas(fig,'AlphavsCm.jpg')
```

Sample post and pre filter plot

```
figure
plot(time1(2445:16509), -1*lift1(2445:16509))
hold on
fig=plot(time1(2745:16509),filterL1(301:end),'k' );
legend("Data","Filtered Data")
title("Filtered Data and Unfiltered Data")
%saveas(fig,'filter.jpg')
```

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