

Aerodynamics III, Lab 5

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The lab evaluates the performance of a fixed-pitch NACA 4412 propeller using experimental testing in a low-speed wind tunnel and analytical modeling. The propeller was made via SolidWorks modeling and a 3D printer, and tested at a constant rotational speed of 4000 RPM across a range of freestream velocities. Experimental measurements of thrust, torque, rotational speed, dynamic pressure, and ambient conditions were used to calculate non-dimensional performance coefficients, including thrust coefficient (C_T), power coefficient (C_P), advance ratio (J), and propulsive efficiency (η_p). Analytical predictions based on blade element theory and airfoil lift and drag data were generated for comparison. Results indicate that thrust decreases with increasing advance ratio, while power varies more gradually, producing peak propulsive efficiency within a narrow band of J . Differences between experimental and analytical results were attributed to manufacturing imperfections, turbulent assumptions not being taken into account, and measurement uncertainties. Overall, the lab provides a characterization of propeller performance and identifies the operating conditions for optimal efficiency, demonstrating the usefulness of combining experimental testing with analytical modeling.

Nomenclature

C_T	=	Thrust coefficient
C_P	=	Power coefficient
C_L	=	Section lift coefficient
C_D	=	Section drag coefficient
D	=	Propeller diameter
J	=	Advance ratio, $J = \frac{V_\infty}{nD}$
N	=	Number of blades
P	=	Shaft power
Q	=	Shaft torque
R	=	Propeller radius
T	=	Thrust
V_0	=	Freestream velocity
Ω	=	Angular speed, $\Omega = 2\pi n$
n	=	Rotational speed (rev/s)
r	=	Radial coordinate along the blade
$\bar{r}$	=	Non-dimensional radius, $\bar{r} = r/R$
c	=	Local blade chord
σ	=	Propeller solidity, $\sigma = \frac{Nc}{\pi R}$
α	=	Section angle of attack
θ	=	Local blade pitch angle
ϕ	=	Inflow angle at the blade element
η_p	=	Propulsive efficiency
ρ	=	Air density
q_∞	=	Freestream dynamic pressure

I. Introduction

This group project assesses the performance of a fixed pitch propeller in a low speed wind tunnel using non-dimensional performance coefficients and polynomial curve fits. Experimental data consisting of dynamic pressure, tunnel temperature, ambient pressure, thrust, torque, and rotational frequency are reduced to advance ratio J , thrust coefficient C_T , power coefficient C_P , and propulsive efficiency η_p . Lines of best fit are then applied to the C_T - J , C_P - J , and η_p - J data to smooth measurement scatter and provide simple analytic expressions for propeller performance. The resulting curves are used to describe overall trends, quantify the operating range over which the propeller is most effective, and identify the advance ratio that maximizes propulsive efficiency for the tested configuration.

II. Methodology

A. Experimental Data Collection

The propeller was fabricated using a 3D printer and inspected to ensure sufficient dimensional accuracy and structural integrity. The complete propeller can be seen in Fig. 3. The experimental data was collected in the university's subsonic wind tunnel using a dedicated propeller testing rig. A rotational speed of 4000 RPM was selected for the propeller, and this value held constant throughout the entirety of data collection. This will allow a direct comparison between theory and experimental results. The propeller was mounted onto the hub of the testing rig, and was ensured to be properly fixed and secure. The orientation of the blades was checked before testing to guarantee that the pitch was facing the correct direction during rotation for positive thrust to be generated. The Gamma ATI load cell was zeroed without any aerodynamic load applied. The hall effect sensor was also tested before the data was collected by spinning the motor briefly to check for a rotational speed measurement. The wind tunnel's dynamic pressure and temperature sensors were activated, as well as the digital ambient temperature barometer. All data channels were simultaneously monitored through the tunnel's data acquisition system.

After setting up all sensors and methods of data acquisition, the testing commenced. The wind tunnel was set to a series of freestream velocities corresponding to a range of advanced ratios. At each test point, the propeller was spun at a constant 4000 RPM while the flow in the tunnel stabilized. Once steady state conditions were met, data points for thrust, torque, rotational speed, dynamic pressure, temperature, and room pressure were recorded. Data was collected for multiple values of freestream velocity to generate a full performance curve. An experimental flow diagram for this process can be seen below in Fig. 1.

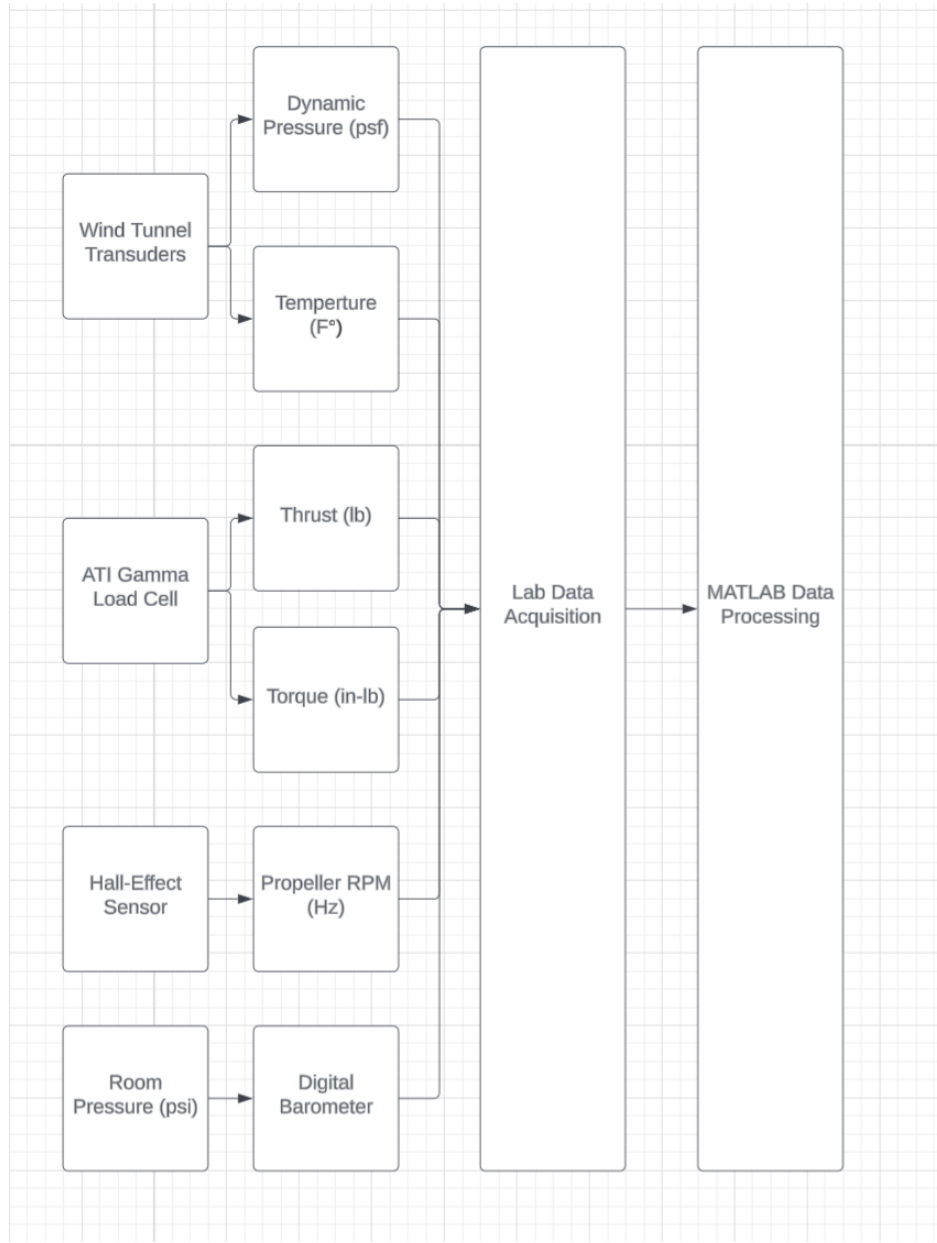


Figure 1: Data collection experimental flow diagram.

B. MATLAB Code

For this lab, the experimental data for the designed NACA 4412 propeller and the analytical data for the propeller are both compared. To calculate the experimental results, the data is converted to SI units. Then, using the ideal gas law, air density is calculated. Over here, R is the gas constant for air.

$$\rho = \frac{p}{RT} \quad (1)$$

In the above equation, atmospheric pressure and wind tunnel temperature is utilized. Using the density of air and the dynamic wind tunnel pressure, free stream velocity is calculated.

$$V_{\infty} = \sqrt{\frac{2T}{\rho}} \quad (2)$$

Next, the rate of rotation of the propeller in hertz is calculated using equation (3). The rate of rotation N , propeller diameter D , and the free stream velocity are then used to calculate propeller advanced ratio J .

$$N = \frac{RPM}{60} \quad (3)$$

$$J = \frac{V_\infty}{ND} \quad (4)$$

Thrust and power coefficients are important in analysis of the propeller performance. Hence, using the calculated variables above and the experimental thrust data, the the thrust coefficient is calculated. Over here, T stands for experimental thrust.

$$C_T = \frac{T}{\rho N^2 D^4} \quad (5)$$

During the experiment the power is not measured. Hence, to calculate both power and power coefficient, the measured torque Q is utilized in the following equations.

$$P = 2\pi NQ \quad (6)$$

$$C_P = \frac{P}{\rho N^3 D^5} \quad (7)$$

To calculate analytical values for the NACA 4412 propeller, lift and drag coefficient data is needed. This data is available in NACA airfoil library. Apart from that, the propeller diameter, radius, chord, advanced ratio, number of blades, and the angle of attack are assumed the same as the experimental propeller.

For the analytical data, the differential thrust coefficient generated by a small radial blade segment is given by the following equation.

$$dC_T = (J^2 + \pi^2 \bar{r}^2) \sigma (C_\ell \cos \phi - C_d \sin \phi) d\bar{r}. \quad (8)$$

The term $(J^2 + \pi^2 \bar{r}^2)$ captures the combined axial and rotational velocity components, while σ scales the aerodynamic load according to the propeller's geometry. The quantity $(C_\ell \cos \phi - C_d \sin \phi)$ projects the sectional lift and drag forces into the thrust direction, and $d\bar{r}$ accounts for the width of the radial element being considered. The differential power coefficient, describing the torque and power contribution of the same blade element, is expressed as the following equation.

$$dC_P = \pi \bar{r} (J^2 + \pi^2 \bar{r}^2) \sigma (C_\ell \sin \phi + C_d \cos \phi) d\bar{r}. \quad (9)$$

In this equation, $\pi \bar{r}$ converts aerodynamic forces into a moment about the propeller axis. As with the thrust expression, the velocity terms and solidity determine the magnitude of the aerodynamic loads. The projection $(C_\ell \sin \phi + C_d \cos \phi)$ identifies the component of lift and drag contributing to torque, producing the elemental power input required to rotate the propeller.

The propeller solidity σ , which characterizes the ratio of total blade area to the area swept by the propeller disk, is defined as the following equation.

$$\sigma = \frac{Nc}{\pi R}, \quad (10)$$

where N is the number of blades, c is the blade chord, and R is the propeller radius. A higher solidity corresponds to a more heavily loaded propeller, increasing both thrust and power demand.

The inflow angle ϕ , which determines the direction of the relative wind seen by each blade element, is given by

$$\phi = \arctan\left(\frac{V_0}{V_2}\right), \quad (11)$$

where V_0 is the freestream velocity and V_2 is the rotational (tangential) velocity at the blade element. This angle directly influences the local angle of attack and therefore the lift and drag forces produced.

The rotational speed of the propeller in radians per second is calculated using equation (12). This speed can be multiplied by the local radius or the position on the propeller to get the local speed in meters per second.

$$\Omega = \frac{2\pi \text{ RPM}}{60}. \quad (12)$$

This conversion enables the tangential velocity and inflow angle to be computed consistently in SI units. The radial coordinate $\bar{r}$ used in Eqs. (1) and (2) is nondimensional, defined as the ratio of the local radius to the propeller tip radius, and spans the interval $0 \leq \bar{r} \leq 1$.

C. 3D Modeling

To model the propeller, both SolidWorks and AirfoilTools was used. The NACA 4412 was selected, and its coordinate data was exported and imported into SolidWorks using the Curve Through XYZ Points tool. After the hub was modeled, planes were placed at the outer diameter, and then several intermediate points along the radius of the propeller. The Curve Through XYZ Points tool was then utilized to sketch on each plane, creating multiple cross sections of the finalized propeller. A 3D curve connecting all of the cross sections leading and trailing edge was drawn to aid the loft tool, which was used to connect each cross section of the propeller.

The Airfoil in SolidWorks is shown in Fig. 2. The printed model is shown in Fig. 3.

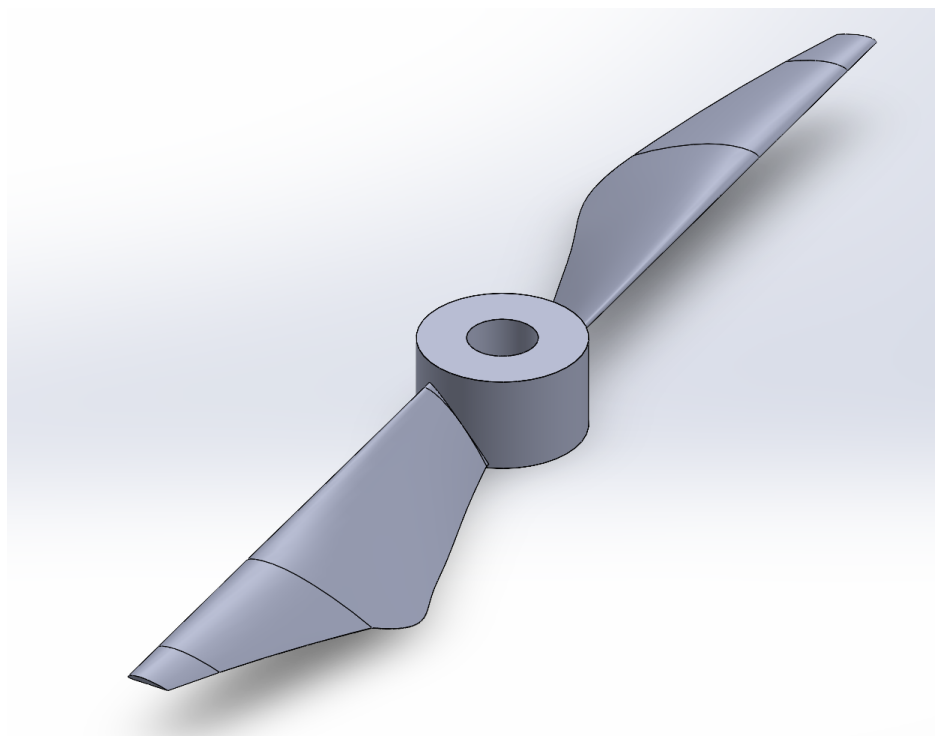


Figure 2: Propeller model in SolidWorks.

III. Results and Discussion



Figure 3: Fabricated propeller.

Using the MATLAB calculated results, multiple graphs were plotted to analyze the experimental and analytical propeller performance and compare and contrast between them.

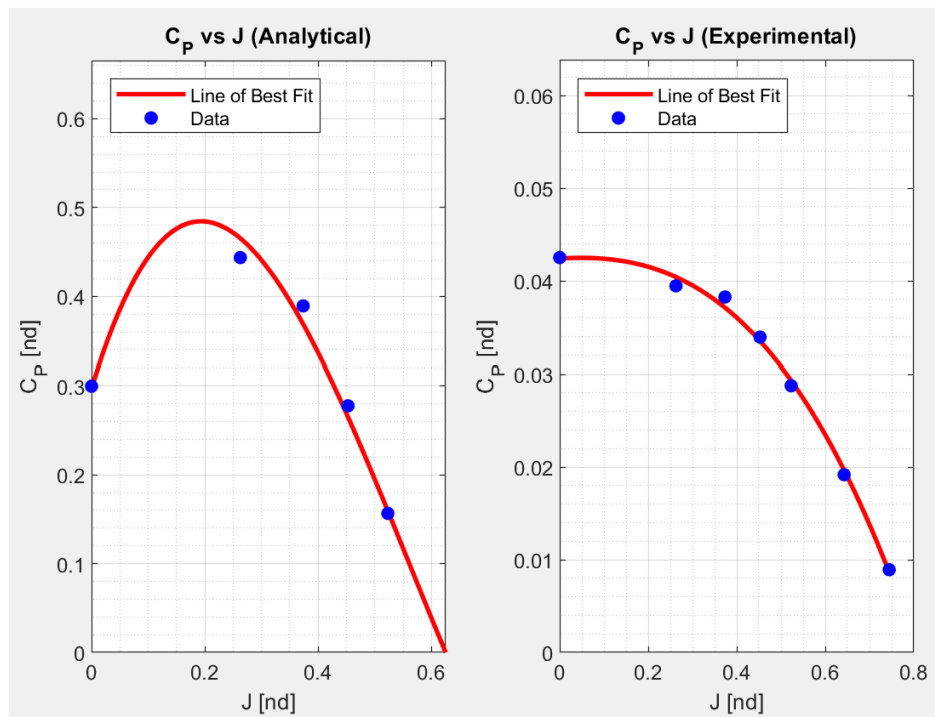


Figure 4: Coefficient of power vs. advanced ratio.

Fig. 4 shows the analytical and experimental coefficient of power as a function of the advanced ratio. The analytical line of best fit shows a peak at around .48, and the experimental line of best fit has a peak around .42. Both graphs show an overall downward trend, with a high advanced ratio corresponding to a low power coefficient. Differences between the experimental and Analytical plots have several factors, including manufacturing/print error, causing unexpected turbulence from surface finish on the blades, or an error in the calculation of the analytical plot, possibly due to neglecting certain forces experienced in the experimental. A peak coefficient of pressure at low through moderate advanced ratios aligns with expected propeller behavior, where blades operate at higher angles of attack and produce more aerodynamic resistance. As the propeller unloads at higher advanced ratios, the power requirement will drop.

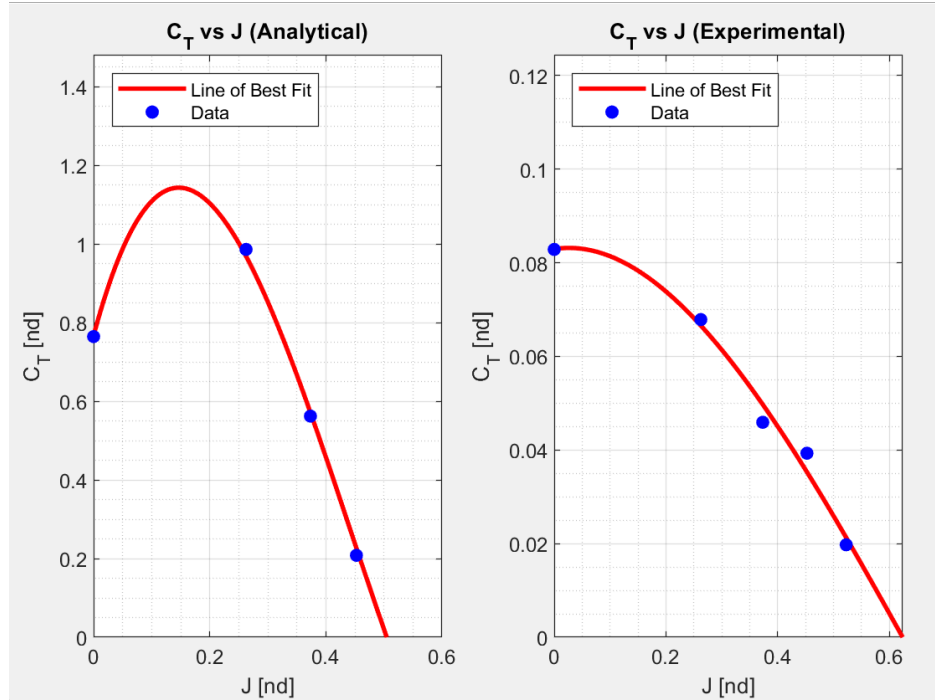


Figure 5: Coefficient of thrust vs. advanced ratio.

Fig. 5 shows the analytical and experimental coefficient of thrust as a function of the advanced ratio. The maximum thrust coefficient achieved was approximately 0.085, whereas the theoretical maximum thrust coefficient, according to the line of best fit, is around 1.15. This shows that the theoretical maximum thrust is around 13.5 times the experimental maximum thrust. This vast difference can be accounted for by several factors. The manufactured propeller was 3D printed. Hence, it had high surface roughness and minor warps. This could have reduced the generated thrust significantly. Additionally, tip vortices and losses could have amounted to a big loss in the experimental thrust. Lastly, the vast difference in data could also have been due to experimental setup errors. The load cell could have been wired incorrectly or could not have been calibrated propeller, resulting in such a drastic difference. However, both plots show a downward trend in thrust generated as the propeller advance ratio increases.

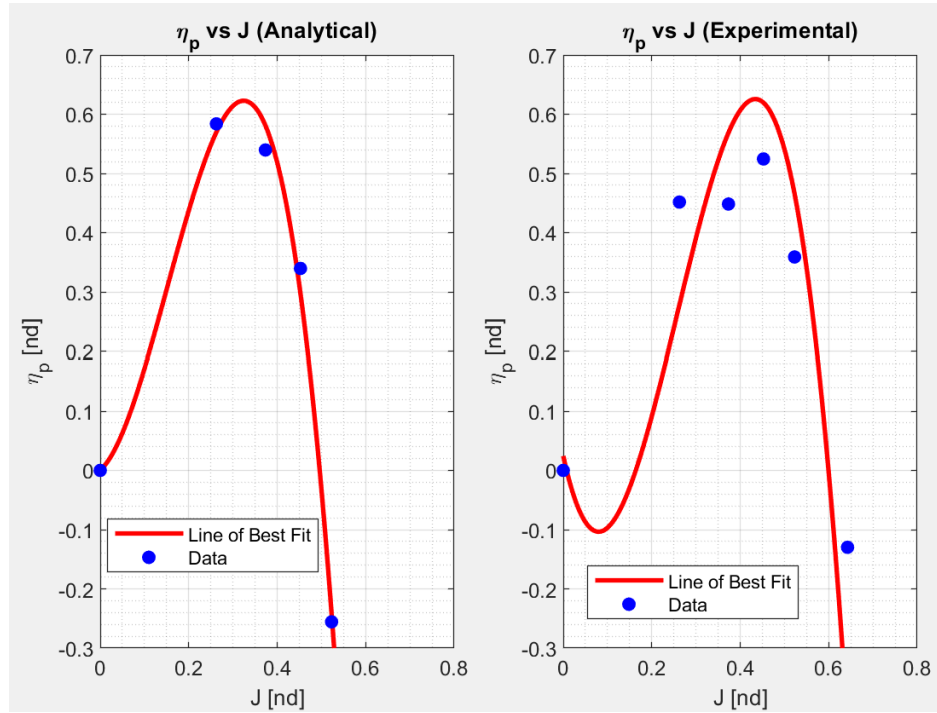


Figure 6: Efficiency vs. advanced ratio.

Fig. 6 shows the analytical and experimental propeller efficiency as a function of the advanced ratio. Both the experimental and analytical data form a bell-shaped curve. Both graphs achieve a peak efficiency of 0.62. However, the peak of the analytical graph is reached around an advance ratio of 0.35, whereas for the experimental graph, the peak efficiency is achieved at an advance ratio of 0.425. Apart from that, the experimental curve shows a negative efficiency initially, which is not present in the analytical curve. As mentioned earlier, the experimental propeller was 3D printed, which could have resulted in a rough surface texture and minor warps, causing a difference in the propeller efficiency. Furthermore, tip losses could account for the negative efficiencies seen in the figure above.

IV. Conclusion

The experiment met its goal of characterizing the performance of a fixed-pitch propeller using non-dimensional coefficients and simple analytical fits. Experimental measurements were reduced to Advance ratio J , Thrust coefficient C_T , Power coefficient C_P , and propulsive efficient η_p . Fig.4 and fig.5 showed that thrust decreased with increasing J while power varied more gradually, indicating the propeller produced its highest thrust at lower advance ratios but continued to draw power across the full range of test conditions. Lines of best fit provided smooth analytical curves that captured the overall behavior and made the underlying trends easier to interpret rather than raw scattered data.

The efficiency η_p results included the analytical and experimental curves in fig.6, showing a clear peak in propulsive efficiency over a relatively narrow band of J , with efficiency dropping at both lower and higher advance ratios. This identified a optimal spot where the propeller converted shaft power to thrust most effectively.

Several sources of error contributed to the difference between analytical and experimental performance. The 3D printed propeller caused geometric deviations and surface roughness that could have caused unexpected turbulence on the blade. Additional differences could have been caused from aerodynamic losses such as tip vortices. These would have further reduced the experimental thrust and efficiency relative to the theoretical predictions.

V. Appendix

A. MATLAB Code

```
clear; clc; close all;

%% EXPERIMENTAL DATA

dataFile = LabDATA.xlsx ;
rawData = readmatrix(dataFile);

q_tunnel = rawData(:,3);
T_airF    = rawData(:,4);
p_airPSI  = rawData(1,5);
rpm_hz    = rawData(:,6);
F_exp     = rawData(:,7);
M_exp     = rawData(:,8);

D_in = 10;

q_tunnel = q_tunnel * 47.88026;
T_air    = (T_airF - 32) * (5/9) + 273.15;
p_air    = p_airPSI * 6894.75729;
F_exp    = F_exp * 4.44822;
M_exp    = M_exp * 0.11298483;
D        = D_in * 0.0254;

R = 287;
rho_air = p_air ./ (R .* T_air);

N = rpm_hz;

Vinf = sqrt((2 .* q_tunnel) ./ rho_air);

J = Vinf ./ (N .* D);

CT_exp = F_exp ./ (rho_air .* N.^2 .* D.^4);

P_exp = 2 .* pi .* N .* M_exp;
CP_exp = P_exp ./ (rho_air .* N.^3 .* D.^5);

eta_exp = (CT_exp .* J) ./ CP_exp;

J    = real(J);
CT_exp = real(CT_exp);
CP_exp = real(CP_exp);
eta_exp = real(eta_exp);

%% EXPERIMENTAL PLOTS

figure(1); hold on; grid on
scatter(J, CT_exp, 'filled', 'o')
xlabel('J')
ylabel('C_T')
title('C_T vs J (Experimental)')
```

```

figure(2); hold on; grid on
scatter(J, CP_exp, 'filled', 'o')
xlabel('J')
ylabel('C_P')
title('C_P vs J (Experimental)')

figure(3); hold on; grid on
scatter(J, eta_exp, 'filled', 'o')
xlabel('J')
ylabel('\eta_p')
title('\eta_p vs J (Experimental)')

%% ANALYTICAL MODEL

numBlades = 2;
R_in = 5;
c_in = 0.8464;

r_in = [0.6419522328;
        1.2839044660;
        1.9258566990;
        2.5678089310;
        3.2097611640;
        3.8517133970;
        4.4936656300];

r_bar = [0.1428571429;
         0.2857142857;
         0.4285714286;
         0.5714285714;
         0.7142857143;
         0.8571428571;
         1.0000000000];

theta = [42.25873;
         33.85051;
         26.41766;
         19.84702;
         14.03857;
         8.90391;
         4.36487];

c = c_in * 0.0254 * ones(size(r_in));
r = r_in * 0.0254;
R = R_in * 0.0254;

dr = r_bar(2) - r_bar(1);

foil = readmatrix('xf-naca4412-il-50000.xlsx');
alphaTab = foil(:,1);
CLtab = foil(:,2);
CDtab = foil(:,3);

good = isfinite(alphaTab) & isfinite(CLtab) & isfinite(CDtab);
alphaTab = alphaTab(good);

```

```

CLtab = CLtab(good);
CDtab = CDtab(good);

CLfit = polyfit(alphaTab, CLtab, 3);
CDfit = polyfit(alphaTab, CDtab, 2);

amin = min(alphaTab);
amax = max(alphaTab);

CT_th = NaN(length(J),1);
CP_th = NaN(length(J),1);
eta_th = NaN(length(J),1);

for j = 1:length(J)
    V = Vinf(j);
    omg = 2*pi*N(j);

    dCTsum = 0;
    dCPsum = 0;

    for k = 1:length(r)
        rr = r(k);
        rb = r_bar(k);
        cc = c(k);

        sol = (numBlades * cc) / (pi * rr);
        Vtan = omg * rr;
        if Vtan <= 0, continue; end

        phi = atan(V / Vtan);
        aoa = theta(k) - phi * 180/pi;
        aoa = min(max(aoa, amin), amax);

        CL = polyval(CLfit, aoa);
        CD = polyval(CDfit, aoa);

        A = J(j)^2 + (pi^2)*(rb^2);

        dCT = A * sol * (CL*cos(phi) - CD*sin(phi)) * dr;
        dCP = pi*rb * A * sol * (CL*sin(phi) + CD*cos(phi)) * dr;

        dCTsum = dCTsum + dCT;
        dCPsum = dCPsum + dCP;
    end

    CT_th(j) = numBlades * dCTsum;
    CP_th(j) = numBlades * dCPsum;

    eta_th(j) = (CP_th(j) > 0) .* (CT_th(j) ./ J(j) ./ CP_th(j));
end

%% ANALYTICAL PLOTS

figure(4); hold on; grid on
scatter(J, CT_th, 'filled')

```

```

xlabel('J')
ylabel('C_T')
title('C_T vs J (Analytical)')

figure(5); hold on; grid on
scatter(J, CP_th, 'filled')
xlabel('J')
ylabel('C_P')
title('C_P vs J (Analytical)')

figure(6); hold on; grid on
scatter(J, eta_th, 'filled')
xlabel('J')
ylabel('\eta_p')
title('\eta_p vs J (Analytical)')

%% COMPARISON PLOTS

J(J < 0) = 0;
[Js, idx] = sort(J);

CTe = CT_exp(idx);
CPe = CP_exp(idx);
etae = eta_exp(idx);

CTt = CT_th(idx);
CPt = CP_th(idx);
etat = eta_th(idx);

goodCT = isfinite(Js) & isfinite(CTt);
goodCP = isfinite(Js) & isfinite(CPt);
goodEta = isfinite(Js) & isfinite(etat);

Jfine = linspace(0, max(Js), 300).';

figure;
tiledlayout(1,2,'Padding','compact','TileSpacing','compact')
nexttile;
pt = polyfit(Js(goodCT), CTt(goodCT), 3); ft = polyval(pt, Jfine);
plot(Jfine, ft, 'r-', 'LineWidth', 2); hold on;
scatter(Js(goodCT), CTt(goodCT), 35, 'filled', 'MarkerFaceColor','b')
grid on; grid minor
xlabel('J')
ylabel('C_T')
ylim([0 max(CTt)*1.5])
title('C_T vs J (Analytical)')
nexttile;
pe = polyfit(Js, CTe, 3); fe = polyval(pe, Jfine);
plot(Jfine, fe, 'r-', 'LineWidth', 2); hold on;
scatter(Js, CTe, 35, 'filled', 'MarkerFaceColor','b')
grid on; grid minor
xlabel('J')
ylabel('C_T')
ylim([0 max(CTe)*1.5])
title('C_T vs J (Experimental)')

```



```

figure;
 tiledlayout(1,2,'Padding','compact','TileSpacing','compact')
 nexttile;
 pt = polyfit(Js(goodCP), CPt(goodCP), 3); ft = polyval(pt, Jfine);
 plot(Jfine, ft, 'r-', 'LineWidth', 2); hold on;
 scatter(Js(goodCP), CPt(goodCP), 35, 'filled', 'MarkerFaceColor','b')
 grid on; grid minor
 xlabel('J')
 ylabel('C_P')
 ylim([0 max(CPt)*1.5])
 title('C_P vs J (Analytical)')
 nexttile;
 pe = polyfit(Js, CPe, 3); fe = polyval(pe, Jfine);
 plot(Jfine, fe, 'r-', 'LineWidth', 2); hold on;
 scatter(Js, CPe, 35, 'filled', 'MarkerFaceColor','b')
 grid on; grid minor
 xlabel('J')
 ylabel('C_P')
 ylim([0 max(CPe)*1.5])
 title('C_P vs J (Experimental)')

figure;
 tiledlayout(1,2,'Padding','compact','TileSpacing','compact')
 nexttile;
 pt = polyfit(Js(goodEta), etat(goodEta), 3); ft = polyval(pt, Jfine);
 plot(Jfine, ft, 'r-', 'LineWidth', 2); hold on;
 scatter(Js(goodEta), etat(goodEta), 35, 'filled', 'MarkerFaceColor','b')
 grid on; grid minor
 xlabel('J')
 ylabel('\eta_p')
 ylim([-0.3 0.7])
 xlim([0 .8])
 title('\eta_p vs J (Analytical)')
 nexttile;
 pe = polyfit(Js(goodEta), etae(goodEta), 3); fe = polyval(pe, Jfine);
 plot(Jfine, fe, 'r-', 'LineWidth', 2); hold on;
 scatter(Js(goodEta), etae(goodEta), 35, 'filled', 'MarkerFaceColor','b')
 grid on; grid minor
 xlabel('J')
 ylabel('\eta_p')
 ylim([-0.3 0.7])
 xlim([0 .8])
 title('\eta_p vs J (Experimental)')

```

B. Airfoil Coordinates

```

Plane 1
15.409489 -8.869983 0
14.758718 -8.21915 0
14.099058 -7.583716 0
12.753066 -6.359041 0
11.373293 -5.192878 0
9.962405 -4.080608 0
8.515957 -3.02993 0

```

7.030393 -2.047003 0
 5.487044 -1.164162 0
 4.686032 -0.773555 0
 3.861906 -0.422982 0
 3.011111 -0.118603 0
 2.125644 0.125724 0
 1.666909 0.220171 0
 1.190394 0.283822 0
 0.686319 0.29974 0
 0.40939 0.264585 0
 0 0 0
 0.065347 -0.331315 0
 0.211593 -0.52251 0
 0.548536 -0.827908 0
 0.911259 -1.088653 0
 1.285539 -1.329381 0
 2.053658 -1.77696 0
 2.836 -2.199903 0
 3.627233 -2.607448 0
 4.418466 -3.014993 0
 5.999153 -3.833163 0
 7.574506 -4.660571 0
 9.149859 -5.487979 0
 10.720767 -6.323087 0
 12.283674 -7.172052 0
 13.838581 -8.034875 0
 14.613811 -8.470137 0
 15.386375 -8.910017 0

Plane 2

18.036258 -9.359301 0
 17.260783 -8.648642 0
 16.475926 -7.956007 0
 14.878064 -6.624809 0
 13.244547 -5.362103 0
 11.57819 -4.162481 0
 9.874303 -3.034955 0
 8.129132 -1.986735 0
 6.322973 -1.055671 0
 5.38893 -0.649619 0
 4.430492 -0.290429 0
 3.443907 0.014689 0
 2.420728 0.249512 0
 1.89225 0.334481 0
 1.345006 0.383401 0
 0.768676 0.376447 0
 0.454239 0.322503 0
 0 0 0
 0.091128 -0.375028 0
 0.267638 -0.586037 0
 0.667573 -0.917936 0
 1.094718 -1.197564 0
 1.53406 -1.453761 0
 2.433386 -1.926503 0
 3.347725 -2.370406 0

4.271447 -2.796284 0
5.195168 -3.222163 0
7.040735 -4.077526 0
8.880672 -4.943703 0
10.720609 -5.80988 0
12.555854 -6.685069 0
14.382655 -7.576479 0
16.201012 -8.484112 0
17.107845 -8.942434 0
18.011863 -9.406163 0

Plane 3

20.730755 -9.63412 0
19.824304 -8.873443 0
18.908191 -8.133485 0
17.046982 -6.715723 0
15.149062 -5.37669 0
13.217327 -4.110171 0
11.246949 -2.926525 0
9.234062 -1.834038 0
7.158378 -0.87622 0
6.088654 -0.465681 0
4.993812 -0.109009 0
3.869987 0.185508 0
2.708483 0.399224 0
2.110341 0.468789 0
1.492878 0.496918 0
0.845465 0.460821 0
0.494707 0.384761 0
0 0 0
0.120824 -0.417033 0
0.329564 -0.645531 0
0.79535 -0.998936 0
1.289152 -1.292258 0
1.795513 -1.558646 0
2.829491 -2.045842 0
3.878926 -2.499889 0
4.938023 -2.933218 0
5.997119 -3.366547 0
8.113379 -4.237349 0
10.223843 -5.120581 0
12.334307 -6.003814 0
14.43994 -6.897406 0
16.536879 -7.809644 0
18.625122 -8.740528 0
19.666829 -9.21115 0
20.705637 -9.687987 0

Plane 4

23.48 -9.69 0
22.44 -8.89 0
21.38 -8.11 0
19.25 -6.63 0
17.08 -5.23 0
14.87 -3.92 0

12.63 -2.7 0
 10.34 -1.59 0
 7.99 -0.63 0
 6.78 -0.22 0
 5.55 0.12 0
 4.29 0.39 0
 2.99 0.57 0
 2.32 0.62 0
 1.63 0.62 0
 0.92 0.55 0
 0.53 0.45 0
 0 0 0
 0.15 -0.46 0
 0.4 -0.7 0
 0.93 -1.07 0
 1.49 -1.37 0
 2.07 -1.64 0
 3.24 -2.13 0
 4.43 -2.59 0
 5.62 -3.02 0
 6.82 -3.45 0
 9.21 -4.31 0
 11.6 -5.19 0
 13.98 -6.07 0
 16.36 -6.96 0
 18.74 -7.87 0
 21.1 -8.8 0
 22.28 -9.27 0
 23.45 -9.75 0

Plane 5

26.267435 -9.521911 0
 25.082735 -8.692292 0
 23.888479 -7.888928 0
 21.4713 -6.360964 0
 19.017808 -4.93277 0
 16.530869 -3.596468 0
 14.005706 -2.365186 0
 11.438497 -1.249426 0
 8.809173 -0.304324 0
 7.462977 0.081586 0
 6.091934 0.399232 0
 4.692224 0.638114 0
 3.255244 0.774601 0
 2.519554 0.795585 0
 1.764751 0.76406 0
 0.980325 0.651144 0
 0.561355 0.521172 0
 0 0 0
 0.191536 -0.494897 0
 0.470032 -0.750874 0
 1.074805 -1.131552 0
 1.70729 -1.436091 0
 2.352198 -1.706498 0
 3.663038 -2.189551 0

4.989167 -2.630596 0
6.324852 -3.045386 0
7.660537 -3.460176 0
10.329996 -4.295007 0
12.993721 -5.145592 0
15.657447 -5.996176 0
18.316394 -6.859888 0
20.966741 -7.747229 0
23.608487 -8.6582 0
24.926972 -9.120249 0
26.242589 -9.590174 0

Plane 6

29.081208 -9.127723 0
27.750561 -8.279919 0
26.410749 -7.461184 0
23.703628 -5.910922 0
20.961678 -4.471123 0
18.187648 -3.133067 0
15.376957 -1.911288 0
12.525937 -0.817414 0
9.615342 0.087509 0
8.129798 0.444042 0
6.620424 0.724995 0
5.083553 0.91874 0
3.510937 0.999115 0
2.70813 0.986978 0
1.886993 0.916702 0
1.037443 0.756311 0
0.587005 0.594722 0
0 0 0
0.232299 -0.53026 0
0.548005 -0.795989 0
1.225243 -1.182101 0
1.929062 -1.483912 0
2.644796 -1.747933 0
4.096427 -2.212023 0
5.562723 -2.629601 0
7.038185 -3.018111 0
8.513647 -3.40662 0
11.462738 -4.189452 0
14.406329 -4.989726 0
17.34992 -5.790001 0
20.288929 -6.604809 0
23.219689 -7.44578 0
26.142199 -8.312914 0
27.601163 -8.753748 0
29.057377 -9.203303 0

Plane 7

25.107359 -6.692526 0
23.942546 -6.019947 0
22.771007 -5.372466 0
20.407753 -4.152801 0
18.018944 -3.02851 0

15.606598 -1.992065 0
 13.16735 -1.056014 0
 10.698512 -0.230397 0
 8.18596 0.432079 0
 6.907491 0.680491 0
 5.611537 0.863647 0
 4.295407 0.971508 0
 2.953049 0.981483 0
 2.269765 0.941294 0
 1.573031 0.850907 0
 0.855448 0.682714 0
 0.477826 0.528342 0
 0 0 0
 0.217563 -0.442975 0
 0.496325 -0.657552 0
 1.087474 -0.961213 0
 1.698127 -1.192089 0
 2.317522 -1.390336 0
 3.571108 -1.731613 0
 4.835454 -2.032733 0
 6.106525 -2.308754 0
 7.377597 -2.584775 0
 9.918394 -3.141837 0
 12.455156 -3.713958 0
 14.991918 -4.286079 0
 17.525318 -4.870749 0
 20.052665 -5.478008 0
 22.57396 -6.107856 0
 23.832926 -6.429054 0
 25.089874 -6.757782 0

Plane 8

20.984695 -4.623582 0
 19.998084 -4.109926 0
 19.006822 -3.617248 0
 17.010346 -2.694828 0
 14.996196 -1.852127 0
 12.965769 -1.082851 0
 10.916738 -0.397489 0
 8.847243 0.195566 0
 6.747518 0.65226 0
 5.682308 0.811377 0
 4.605005 0.91595 0
 3.51375 0.957587 0
 2.404356 0.917408 0
 1.841288 0.859556 0
 1.268918 0.759747 0
 0.68213 0.594905 0
 0.375714 0.453743 0
 0 0 0
 0.195726 -0.35813 0
 0.433775 -0.525355 0
 0.933126 -0.754911 0
 1.445965 -0.923629 0
 1.96485 -1.065075 0

3.012853 -1.301813 0
4.068296 -1.504986 0
5.128391 -1.68718 0
6.188485 -1.869374 0
8.307744 -2.237957 0
10.424212 -2.619128 0
12.540681 -3.000299 0
14.654823 -3.391959 0
16.764781 -3.8025 0
18.870552 -4.231922 0
19.922275 -4.451878 0
20.972602 -4.678127 0

Plane 9

16.737689 -2.928876 0
15.940535 -2.557111 0
15.14043 -2.202079 0
13.531368 -1.542218 0
11.911094 -0.945946 0
10.280493 -0.408242 0
8.63809 0.062526 0
6.982703 0.459666 0
5.308137 0.748035 0
4.461118 0.836998 0
3.606426 0.882453 0
2.742883 0.877707 0
1.867832 0.807698 0
1.424995 0.742573 0
0.976257 0.64398 0
0.518373 0.493512 0
0.281169 0.371423 0
0 0 0
0.166979 -0.276177 0
0.360809 -0.400076 0
0.763222 -0.564204 0
1.174192 -0.679805 0
1.588997 -0.773651 0
2.4251 -0.924529 0
3.265923 -1.048634 0
4.109698 -1.156004 0
4.953472 -1.263374 0
6.64043 -1.481461 0
8.325618 -1.709589 0
10.010806 -1.937716 0
11.694518 -2.174211 0
13.375575 -2.425766 0
15.053977 -2.692381 0
15.89244 -2.829873 0
16.730018 -2.972384 0

Plane 10

12.391215 -1.614949 0
11.793617 -1.367383 0
11.194387 -1.132205 0
9.991035 -0.699017 0

8.781484 -0.312908 0
 7.566225 0.029839 0
 6.344441 0.32303 0
 5.115481 0.561709 0
 3.875919 0.719859 0
 3.250756 0.75805 0
 2.621352 0.764029 0
 1.987055 0.732841 0
 1.346396 0.653336 0
 1.023131 0.591283 0
 0.696604 0.504451 0
 0.36502 0.379214 0
 0.194661 0.281906 0
 0 0 0
 0.13154 -0.197552 0
 0.277922 -0.282364 0
 0.578841 -0.390041 0
 0.884491 -0.46179 0
 1.192261 -0.517434 0
 1.81139 -0.601464 0
 2.433128 -0.665672 0
 3.056497 -0.717491 0
 3.679867 -0.76931 0
 4.926279 -0.875426 0
 6.171713 -0.988975 0
 7.417146 -1.102524 0
 8.661765 -1.222268 0
 9.904915 -1.353162 0
 11.146597 -1.495206 0
 11.767031 -1.569325 0
 12.386975 -1.647161 0

Plane 11

7.970464 -0.686886 0
 7.581329 -0.545231 0
 7.191497 -0.411546 0
 6.409741 -0.168085 0
 5.625336 0.045091 0
 4.83849 0.230374 0
 4.048856 0.383779 0
 3.256153 0.502118 0
 2.458918 0.568655 0
 2.058 0.575624 0
 1.655269 0.561872 0
 1.250446 0.524211 0
 0.842904 0.455469 0
 0.637878 0.406753 0
 0.431458 0.342098 0
 0.222876 0.252737 0
 0.116632 0.185742 0
 0 0 0
 0.089649 -0.12268 0
 0.185643 -0.172838 0
 0.381116 -0.233304 0
 0.578612 -0.270659 0

0.777015	-0.297654	0
1.175353	-0.33411	0
1.574807	-0.357815	0
1.974958	-0.37355	0
2.37511	-0.389286	0
3.175273	-0.42235	0
3.975017	-0.460197	0
4.774762	-0.498043	0
5.574158	-0.539874	0
6.372927	-0.588878	0
7.171068	-0.645054	0
7.569964	-0.675135	0
7.968651	-0.707606	0