ASEN 2004 LAB 1: Aerodynamic Performance of the Tempest/TTwistor UAS
(Submitted March 7, 2018)

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This report includes the results of using high-fidelity computational fluid dynamics (CFD) to analyze the Tempest/TTwistor battery-powered aircraft. Before the availability of CFD, every design had to be tested in a wind tunnel or in a full-scale setting, and some of those tests were prohibitively expensive or difficult to perform. Now, improved computer technologies have made the use of CFD accessible for most aircraft designers. The data obtained from high-fidelity CFD modeling is sufficient for creating artificial flight data. Artificial data is used in this report to fully characterize the aircraft's flight attributes.

Nomenclature

α	=	Angle of Attack	AR	=	Aspect Ratio
C	=	Battery Capacity	C_L	=	Coefficient of Lift
C_D	=	Coefficient of Drag	D	=	Drag
e	=	Oswald Efficiency Factor	E_{max}	=	Maximum Endurance
i	=	Discharge Rate (Current)	k	=	$\frac{1}{\pi * AR * e}$
L	=	Lift	η	=	Efficiency
n	=	Discharge Parameter	ρ	=	Density
P	=	Power	R_{max}	=	Maximum Range
Rt	=	Battery Hour Rating	S	=	Wing Area
t	=	Time	U	=	Velocity for Maximum Range or Endurance
v	=	Velocity	V	=	Voltage
W	=	Weight			

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I. Introduction

Due to recent improvements in computational simulation, it has become possible to generate flight data in an entirely digital environment. This reduces testing costs and streamlines the design process. With this synthetic flight data, it is possible to estimate the theoretical performance of the aircraft using more traditional analyses. These include relationships such as the drag polar. For this investigation, we are using synthetic data for the Tempest unmanned aircraft system (UAS). This aircraft is electrically powered, using two Lithium polymer batteries. Battery information was taken from the TTwistor, another UAS. In addition to modeling and analyzing flight performance for this aircraft, we also investigate the performance of the batteries, and the expected range and endurance offered by the propulsion apparatus. This will allow us to predict the performance of the hybrid Tempest/TTwistor UAS.

II. Theory

The performance of the aircraft was characterized using the below relations. Many of the equations presented operate as estimates, though they are assumed ideal for the purposes of this investigation. All cases lie within the incompressible regime.

The following equations are referenced from the Anderson textbook, Introduction to Flight [1].

Coefficient of Drag including parasite and induced drag:

$$C_D = C_{d0} + \frac{C_l^2}{\pi e AR} \tag{1}$$

Shifted Coefficient of Drag including parasite and induced drag using minimum drag rather than drag at zero lift:

$$C_D = C_{d_{min}} + \frac{(C_l - C_{l_{mindrag}})^2}{\pi e AR} \tag{2}$$

For straight and level flight the Lift must balance the weight of the aircraft:

$$L = W = C_L \frac{1}{2} \rho_\infty v_\infty^2 S \tag{3}$$

Similarly, for straight and level flight the thrust is equivalent to the total drag on the aircraft:

$$T = D = \frac{1}{2} \rho_\infty v_\infty^2 S \left(C_{d_{min}} + \frac{(C_l - C_{l_{mindrag}})^2}{\pi e AR} \right) \tag{4}$$

Rate of climb is dependent on excess power available which is not going toward counter-acting drag and the weight of the aircraft:

$$R/C = \frac{P_a - Preq}{W} \tag{5}$$

Stall speed is the slowest speed the aircraft is able to fly at and still support its own weight at a maximum coefficient of lift:

$$v_{stall} = \sqrt{\frac{2W}{C_{L_{max}} \rho_\infty S}} \tag{6}$$

The following equations are referenced from the Traub paper, Range and Endurance Estimates for Battery-Powered Aircraft [6].

The endurance is the time in hours that the aircraft's propulsion system can support flight:

$$E = t = Rt^{1-n} \left[\frac{\eta_{tot} V \times C}{\frac{1}{2} \rho U^3 S C_{D0} + (2W^2 k / \rho U S)} \right]^n \tag{7}$$

Range is the distance the aircraft can travel in the time given by the endurance equation:

$$R = E * v * 3.6 \tag{8}$$

Velocity for maximum endurance is found where the airplane is at a minimum power required:

$$U_E = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{k}{3C_{D0}}}} \tag{9}$$

Velocity for maximum range is found where the a straight line is drawn from the origin to the power required curve:

$$U_R = \sqrt{\frac{2W}{\rho S}\sqrt{\frac{k}{C_{D0}}}} \tag{10}$$

The maximum range can easily be calculated by flying at the velocity for maximum range for the entirety of the time period of endurance and is given by:

$$R_{max} = Rt^{1-n}\left(\frac{\eta_{tot}V \times C}{(1\sqrt{\rho S})C_{D0}^{1/4}(2W\sqrt{k})^{3/2}}\right)^n \sqrt{\frac{2W}{S\rho}\sqrt{\frac{k}{C_{D0}}}} * 3.6 \tag{11}$$

As with maximum range, maximum endurance is attained by flying at the velocity for maximum endurance and is given by:

$$E_{max} = Rt^{1-n}\left(\frac{\eta_{tot}V \times C}{(2\sqrt{\rho S})C_{D0}^{1/4}(2W\sqrt{k/3})^{3/2}}\right)^n \tag{12}$$

The equation for battery capacity is given by:

$$t = \frac{Rt}{i^n}\left(\frac{C}{Rt}\right)^n \tag{13}$$

III. Experimental Apparatus and Procedure

The experimental portion of this lab involved interpreting CFD experimental data and plotting various functions to determine important information about the Tempest/TTwistor aircraft systems. The first step was to plot the experimental data from the CFD alongside any relevant theoretical models. Figure (3) shows the experimental data for coefficients of lift and drag alongside the theoretical curves using Equations (1) and (2). Then, the operational point was determined by using Equations (2), (3), and(4) to find the lift and drag coefficients at an altitude of 1829m and a speed of 18m/s. Next, using Equation (5), the available rate of climb was determined at various cruising velocities.

Maximum range and endurance and the optimal velocities associated with each were determined using the given AIAA journal on battery powered aircraft [6]. Equation (12) and (11) allowed for the calculation of the aircraft's maximum endurance and range respectively given the battery and aircraft data provided in the lab documentation. The optimal velocity for range and endurance can be calculated similarly using Equations (10) and (9) respectively.

Determining the effects of the discharge rate of the battery was done using Equation (13) allowing for observation of the Peukert effect.

IV. Summary of Results

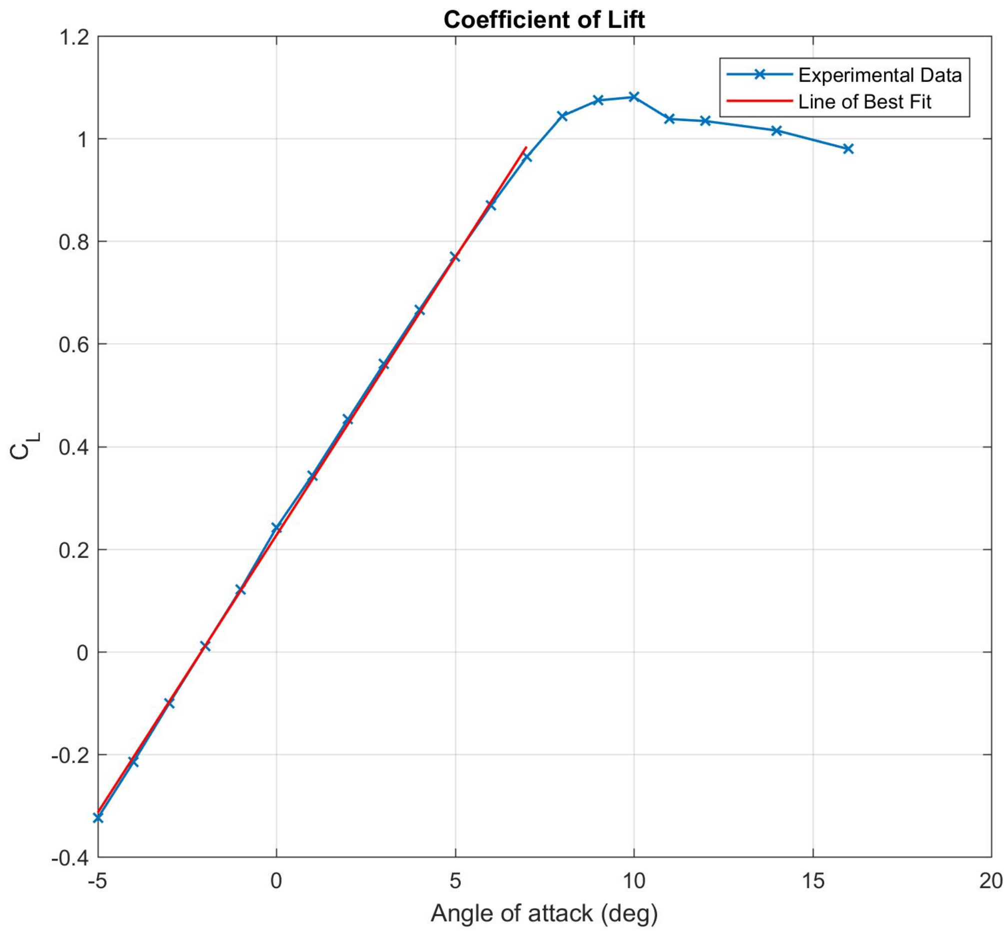
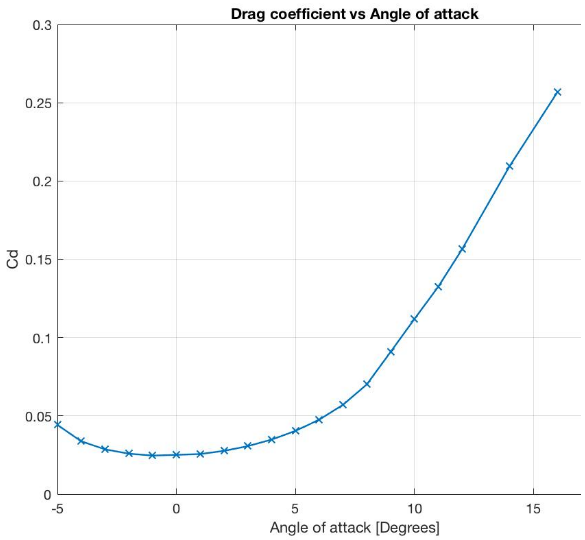


Figure 1: Graph of Lift Coefficient for TTwistor

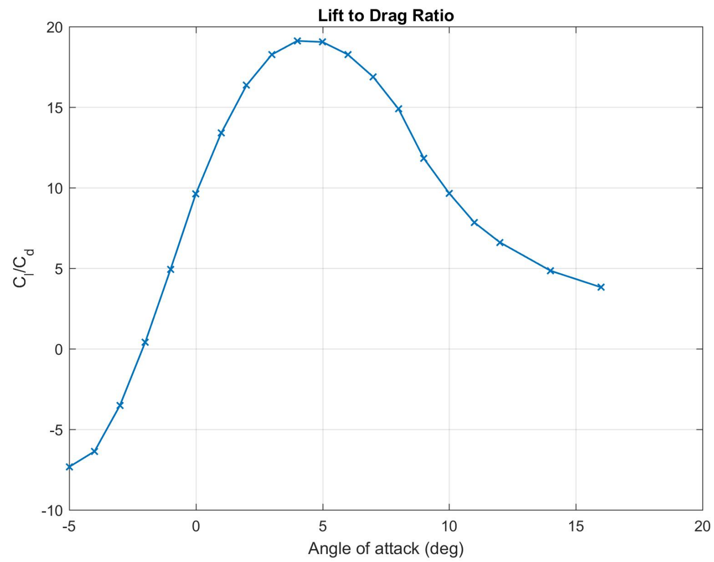
Figure (1) shows how the lift coefficient changes with the angle of attack of the airplane. The linear portion of this graph can be used to create the drag polar. From Figure (1) we can see that the flow starts to separate when the angle of attack is close to 7 degrees, and further the aircraft stall. The non linear portion of the graph is not relevant to the drag polar since standard flight does not occur in the stall portion of this graph. The equation of the line of best fit on the linear portion of the graph is

$$C_L = (0.1082\alpha) + 0.2271 \tag{14}$$

Here, the slope of the line of best fit, 0.1082 deg^{-1} is the finite lift slope for the TTwistor. The experimental data is all from the actual airplane, so there is no need to adjust for a finite wing span, the values are already appropriate for the finite case.



(a) Graph of Drag Coefficient for TTwistor



(b) Graph of Lift to Drag Ratio for TTwistor

The graph above on the left demonstrates how the value of drag increases with angle of attack. This is directly related to the induced drag caused by the additional lift at higher angles of attack. Equations (1) and (2) explicitly link the theoretical values of drag coefficients with lift coefficients.

The ratio of the lift to drag of the airplane gives us information about the performance and efficiency of the aircraft. The maximum value for the ratio of lift over drag dictates the maximum range of the propeller aircraft and at what speed maximum range occurs.

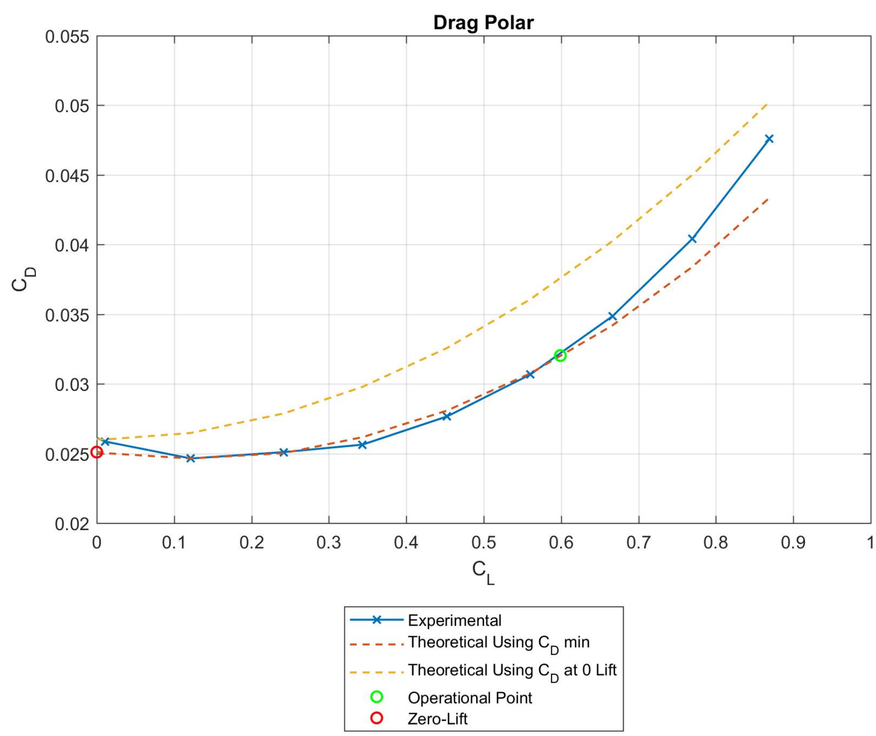


Figure 3: Graph of Drag Polar for TTwistor

The drag polar is a plot of the relationship between the coefficients of lift and drag, accounting for all the induced drag over the finite wings and the inherent drag of the body of the airplane. In the figure above, the blue data points show the experimentally determined values for the coefficients of lift and drag. In yellow, the parabola is defined using Equation 10. The red line is defined by a 'shifted' theoretical drag polar, defined by Equation 11. For the experimental data, the shifted theoretical drag polar matches the data better, using this theoretical value, the approximate coefficient of drag at zero lift is 0.025. The operational point on the drag polar for a cruise speed of 18 m/s is:

$$C_L = 0.5991$$

$$C_D = 0.0320$$

For the calculations in the lab, Equation (1) was used, since all the parameters depend on C_{D0}.

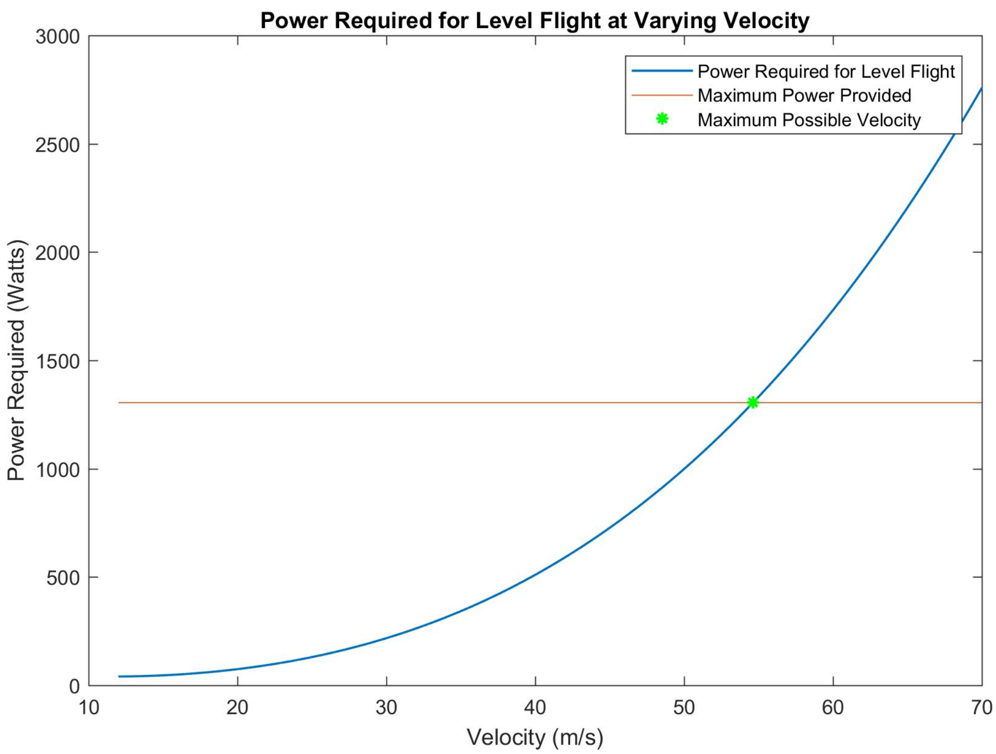


Figure 4: Graph of Power Required for level flight of TTwistor

For level flight, the lift perfectly balances the weight,as in Equation (3). and the thrust required is equal to the total drag, as in Equation (4). The power required is then $P_{req} = v_\infty T_{req}$ and the power available is $P_a = \eta IV$ which is a constant, $1305W$ for the TTwistor. The intersection of P_{req} and P_a is the maximum velocity that can be sustained by the power of the batteries, which is approximately 54.63 m/s for the TTwistor on Earth.

The stall speed of the airplane is the point at which the dynamic pressure produced by the airplane is barely enough to counter the weight of the plane, if it is at a maximum coefficient of lift. It is the slowest speed able to be attained without falling out of the sky. The stall speed is defined by Equation (6). For the TTwistor, this minimum speed is 13.4015 m/s. The difference between max speed and min speed is 41.2285 m/s which defines the range of operational speeds of the TTwistor on Earth.

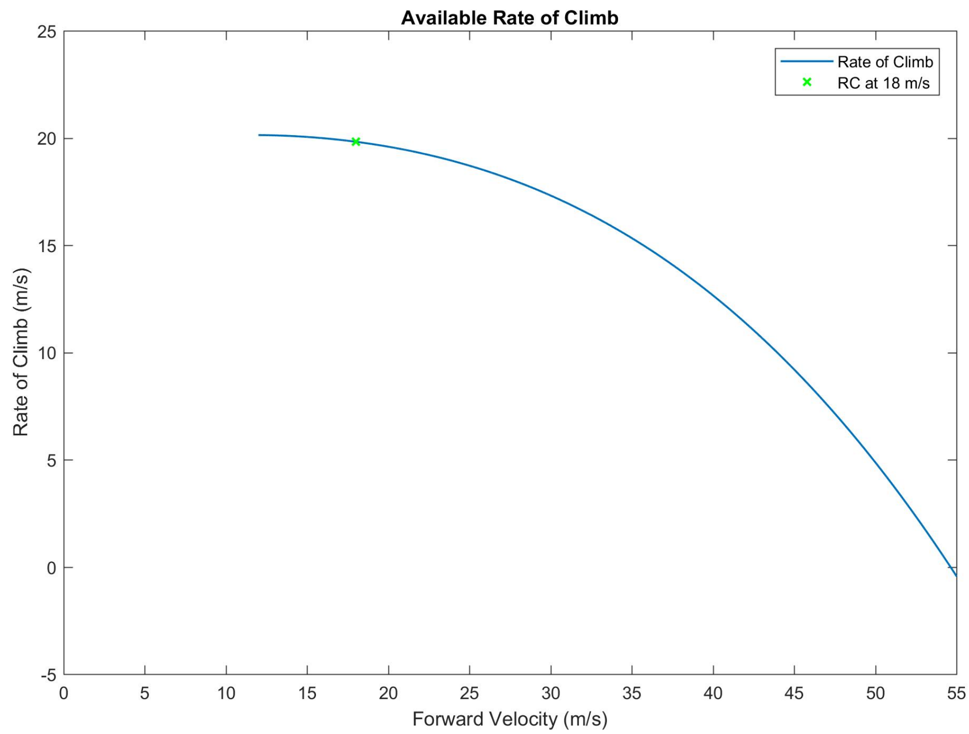


Figure 5: Graph of Rate of Climb for TTwistor

The ability of of an airplane to climb depends on the excess power available which is not being used for forward velocity. Dividing the excess power by the weight yields the highest possible rate of climb available at a given forward velocity, as described in Equation 6. Obviously, this is only the maximum amount the airplane could possibly climb, so it could still climb at a slower rate, for that reason this rate of climb is called the 'available rate' because it is not necessarily the true rate of climb. This maximum rate of climb is 19.83 m/s for the TTwistor when it is at a cruise speed of 18 m/s and is indicated on the figure above by a green marker. As expected, the available rate of climb is zero for the previously calculated v_{max}.

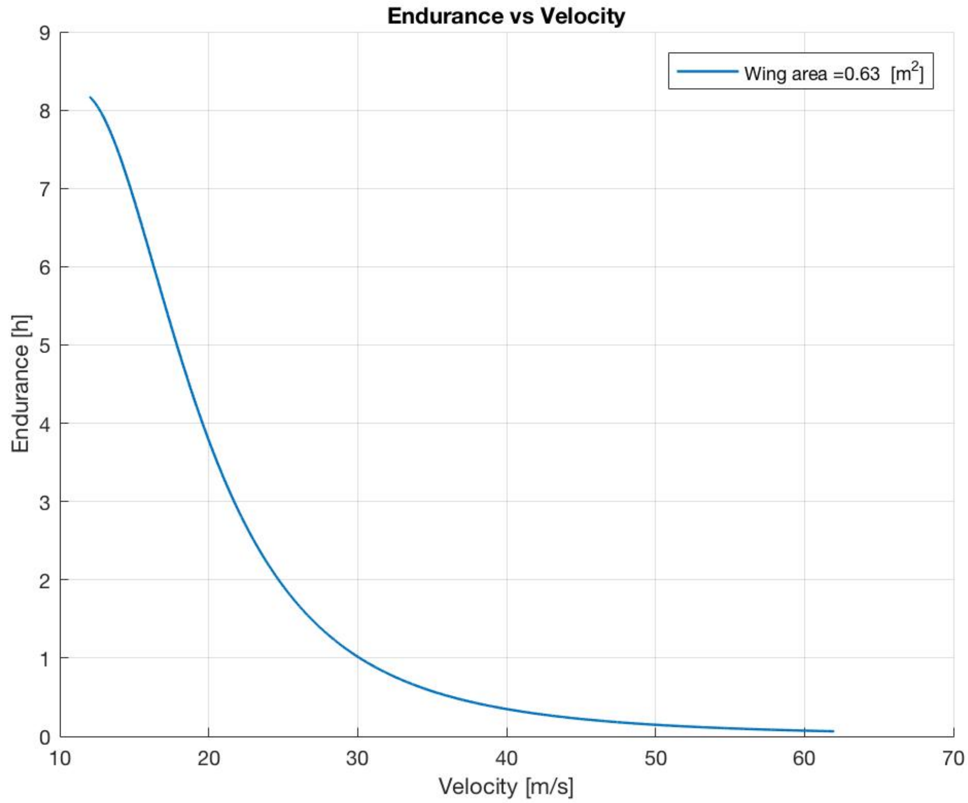


Figure 6: Graph of Endurance for level flight of TTwistor

Using Equations (12) and (9) the maximum endurance calculated was 8.24 h at the speed of 11.3 m/s. Additionally the endurance of the aircraft was calculated using Equation (7) for each velocity and then plotted in Figure (7). The speed for the maximum endurance calculated with Equation (9) is lower than the stall speed, and so it can not be achieved. This is evident in the graph above, as the peak in endurance does not appear since the domain is only speeds higher than the stall speed. In this case the maximum endurance was calculated using Equation (7) at the lowest speed, stall speed. Therefore the maximum endurance is 8.15 h at 13.4 m/s.

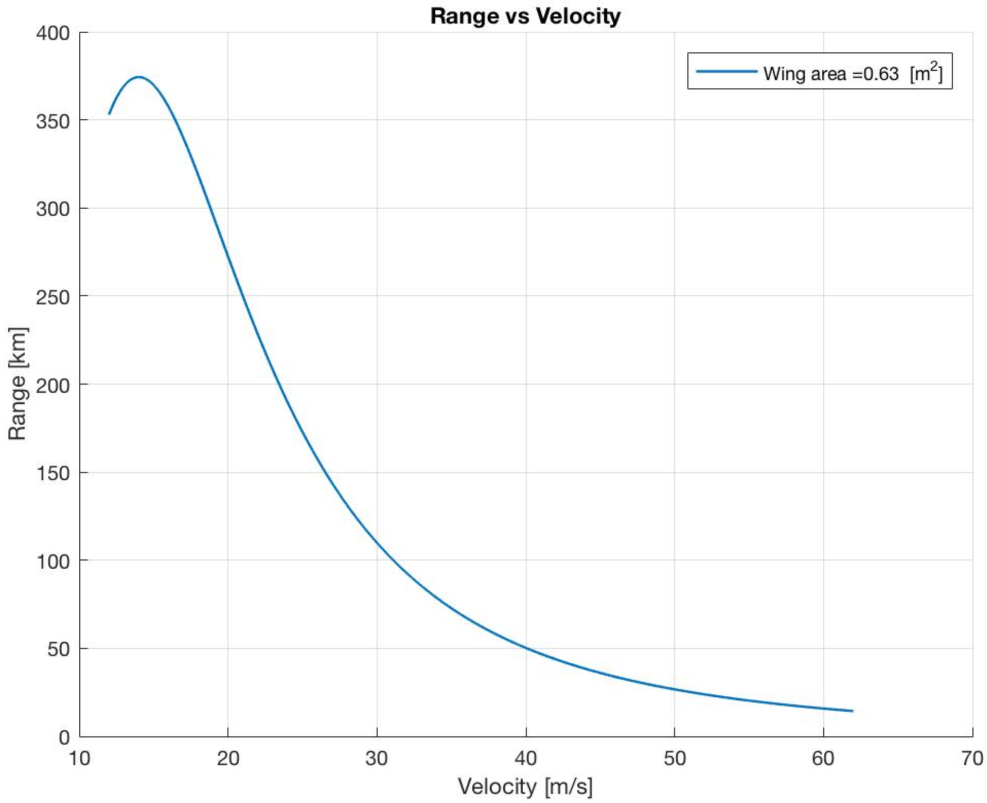


Figure 7: Graph of Range for level flight of TTwistor

Using Equations (11) and (10) the maximum range calculated was 373 km at the speed of 14.5 m/s which is above the stall speed of the airplane so it is achievable. Also the range of the aircraft was calculated using Equation (8) for each velocity and then plotted in Figure (8). We can see that the peak in Figure (8) is really close to the calculated maximum range and the speed for maximum range also lies in the operational range of the TTwistor. Therefore the maximum range is 373 km.

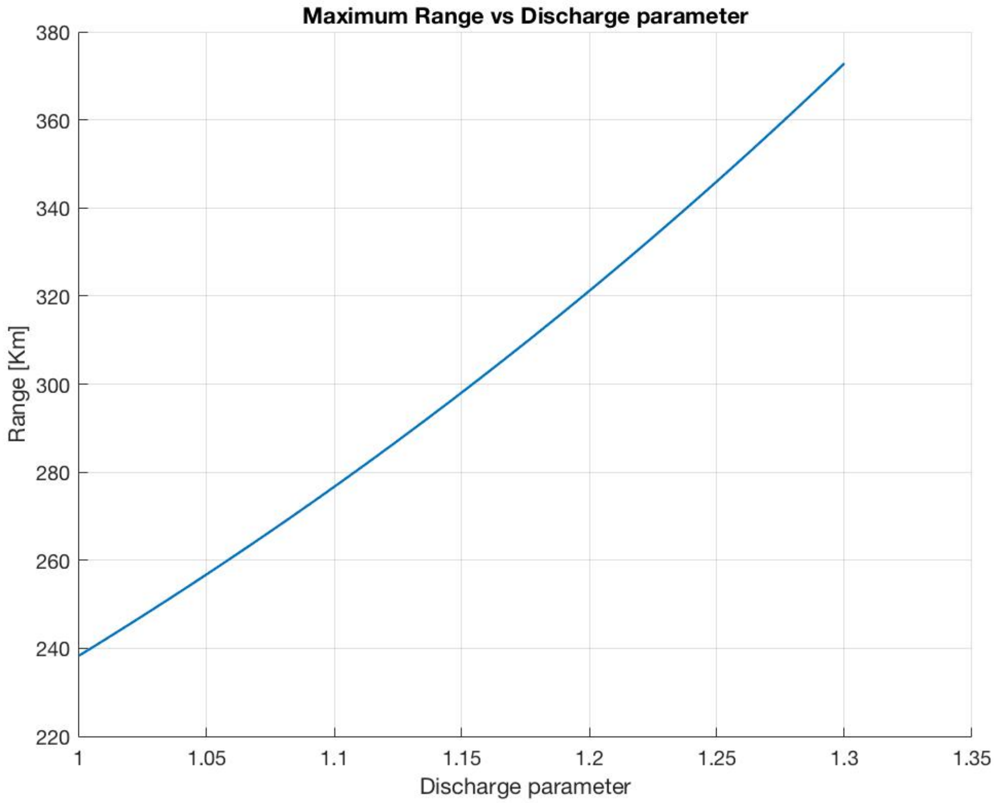


Figure 8: Graph of Maximum Range vs discharge parameter for level flight of TTwistor

Varying the discharge parameter of the battery has a great effect on the performance of the TTwistor. The discharge parameter affects the range and the endurance of the aircraft. The range vs discharge parameter is plotted in figure 9. When the discharge parameter is 1 the aircraft can achieve a maximum range of 238 km. In the other hand when the value of the discharge parameter is maximum, 1.3, the aircraft can achieve a maximum range of 373 km. There is a difference of 135 km in range from the two different discharge parameters, that shows that the performance is optimized with the maximum discharge parameter. The endurance is also optimized with the maximum discharge parameter. For all the analysis of the TTwistor we used a discharge parameter of 1.3.

We did, however, investigate the effects on the effective battery capacity from varying the discharge parameter. A graph showing these effects is shown below.

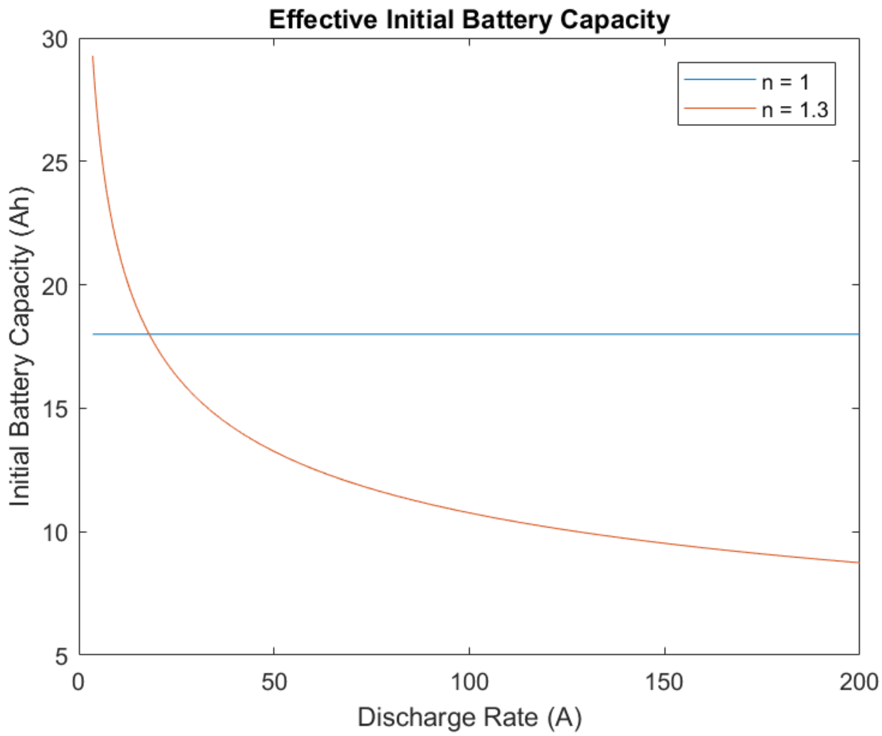


Figure 9: Graph of Effective Battery Capacity vs discharge rate

The initial battery capacity of the TTwistor's batteries remains constant with a discharge parameter of 1. This is the ideal case, of course. With a less than ideal case, such as with a discharge parameter of 1.3, the initial effective battery capacity will decrease as the discharge rate increases.

V. Discussion

Information about the drag polar can be a very useful tool in quantifying and analyzing the performance of an aircraft. Using provided experimental CFD data, a drag polar was constructed to characterize the performance of the Tempest/TTwistor. An experimental drag polar was constructed from the provided Equation (1) above, utilizing the best estimate for the Oswald efficiency. When superimposed with the experimental drag polar and the drag polar using C_D at zero lift in Equation (2), it is easy to tell that the theoretical drag polar constructed using the minimum C_D is a much more accurate theoretical estimate of the drag polar for the Tempest/TTwistor. This newfound drag polar allows us to determine an operation point for the Tempest/TTwistor in order to further characterize the performance of the aircraft.

After comparing variations on the drag polar, required power and available power comparisons are imperative for determining maximum velocity, range, and endurance of the craft. The battery powered propulsion system results in a constant power available. Equating this to the power required allows us to calculate the max velocity of the craft, however determining the max range and endurance of the craft is more complex. The plots above show how range and endurance vary with the velocity of the Tempest/TTwistor, which is an excellent guide to optimal flight conditions given a range of velocities. In comparison with the Tempest performance, the TTwistor has considerably higher range and endurance values for the given cruise speed of 18 m/s.

The combination of these parameters and values is critical to determining both optimal and max performance capabilities of the aircraft, specifically a battery powered aircraft. When used and correlated correctly, these values can provide a plethora of information describing the performance and capabilities of an aircraft. Since the experimental CFD data was only provided to us and not taken by students, it can only be said that some error and uncertainty is inherent in the given data, but cannot be explicitly quantified with numerical uncertainties. However some sources of error could have come from inaccuracies in test equipment, inaccurate CFD modeling, and errors in dimension approximation used in the acquisition of the given data.

VI. Conclusions

The high-fidelity CFD data for the Tempest/TTwistor aircraft was used to characterize the performance of the system. Calculations using this data yields a maximum velocity of 54.6 m/s and a stall speed of 13.4 m/s which gives an operational velocity range of approximately 41 m/s between stall and max speed for the aircraft. Of course, further research could be done on the differences in these values when calculated using CFD versus experimental wind tunnel testing, but for now these values match what might be expected from this aircraft. Another component of the system that was analyzed was the propulsion subsystem, which includes the batteries and motors. Both the CFD data and the equations for endurance and range of a battery-powered aircraft are used to estimate the maximum performance of the dual-motor TTwistor system. The approximate endurance of the battery powered aircraft is 8.15 hrs, flying at stall. The range is dependent on the discharge parameter of the battery– with n= 1.3, the range is approximately 373 km. Realistically, these estimates would likely be shortened by flying slightly faster and in real-world conditions with wind, storm systems, inefficient flight control etc. whose effect could be thoroughly investigated in a future lab.

These estimates cut back on design and testing time and resources. They allow for only the most feasible designs to be fully built and tested rather than building 100's of designs just to determine which one allows for requirement satisfying performance. Computational fluid dynamics is changing the way aircraft designers approach their designs in that it allows for faster changes and more radical designs.

Acknowledgements

Thank you to Professor Brian Argrow, Teaching Assistants: Dr. Larewnce, DeAnna Sewell, Kimia Seyedmadani, Lab Coordinator: Trudy Schwartz, and Course Assistants: MC Dorbecker, Jacob Denton, Andrew Lyons, and Zachary Fester.

References

[1] Anderson, J. D., Introduction to Flight, 8th Ed., McGraw Hill (2012).

[2] Argrow, B. ASEN_2004_Experiment_1_Aero 20180124. Experimental Laboratory 1: Aerodynamic Performance of the Tempest/TTwistor UAS. Spring 2018.

[3] Raymer, D. P, Aircraft Design: A Conceptual Approach, 5th Ed, AIAA Inc, Chap. 12 (2012).

[4] Roadman, J., Elston, J., Argrow, B., and Frew, E., "Mission Performance of the Tempest Unmanned Aircraft System in Supercell Storms," Journal of Aircraft, Vol. 49, No. 6, pp. 1821-1830 2012.

[5] Shevell, R. S., Fundamentals of Flight, 2nd Ed., Prentice Hall, Chap. 11 1989.

[6] Traub, L. W., "Range and Endurance Estimates for Battery-Powered Aircraft," Journal of Aircraft, Vol. 48, No. 2, pp. 703-707 2011.

MATLAB Code

```
% ASEN 2004
% Lab 1
% Aerodynamic Performance of the Tempest/TTwistor UAS

% Purpose: Analysis of TTwistor UAS.x

% Assumptions: Level unbalanced flight.

% Inputs: no.

% Outputs: OUTPUTS CALCULAtED PARAMETERS IN COMAND WINDOW! Also graphs the
% parameters for wing area inputed in variable S.

% Created: 01/19/2018
% Modified: 03/07/2018

%NOTES:
% - Values are outputed in the command window for easy access.

 clear all
 close all
 clc;
%% INITIAL CONDITIONS:
 JumpSize = 60000;

%Earth flight conditions:
 Density = 1.02400617867;
 g = 9.81;
 S = 0.63;  %Earth wing area.

%Each battery weights 0.984, calculate weight of airplane:
W = (6.4)*g; % BASELINE WEIGTH

%Each battery has 50 amps, there are two batteries:
 i = 100;  %[Amps]

%Airplane conditions:
AR = 16.5;
 ntot = 0.5;

%Battery conditions
 Volts = 26.1;
 Rt = 1;    %[hour]
 C = 18;    %[Amps*hour]
 n = 1.0;

%Minimum coefficients at alpha = 1 degree, where we have the minimum drag.
 CLmin = 0.1216;
 CDmin = 0.02464;
 CD0 = 0.02511;

% All data from the lab instructions.
 alpha = [ -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 14 16];
```

```
cl = [-0.32438 -0.21503 -0.10081 0.010503 0.12155 0.24163 0.34336 0.45256 0.56037 0.66625 0
cd = [0.044251 0.033783 0.028627 0.025864 0.024643 0.025099 0.025635 0.02766 0.030677 0.034

%Cut data of the linear part of Cl vs Alpha.
alpha2 = [ -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 ];
cl2 = [-0.32438 -0.21503 -0.10081 0.010503 0.12155 0.24163 0.34336 0.45256 0.56037 0.66625
cd2 = [0.044251 0.033783 0.028627 0.025864 0.024643 0.025099 0.025635 0.02766 0.030677 0.03

%% INITIAL CALCULATIONS
%Get Oswald efficiency factor:
Oswald = 1.78*(1-0.045*AR.^(0.68))-0.64;

%Get k:
k = 1/(pi*AR*Oswald);

%Get the Drag coefficient for plot.:
CL = linspace(-0.4,1.2,5801);
%CD = CD0 + k*CL .^2;
CD = CDmin + k.*(CL - CLmin).^2;

%Fit linear portion of Cl:
coeff = polyfit(cl2,cd2,2);

Cd_fit = coeff(1).*CL.^2+coeff(2).*CL+coeff(3);

%Bsterry: get t.
t = Rt/(i^n)*(C/Rt)^n;

%Get the maximum power provided by the batteries.
Pmax = (Volts * C /Rt*(Rt/t)^(1/n))*0.5;

%Get the t for each element in the array
tg = Rt/(i^n)*(C/Rt)^n;

%Get array of discharges rates to see how power varies
ns = linspace(1,1.3);

%% INITIALIZE:

%Initialize 1 dimensional arrays.
Stall_Speed = zeros(1,length(S));
vE = zeros(1,length(S));
vR = zeros(1,length(S));
Emax = zeros(1,length(S));
Rmax = zeros(1,length(S));
RCmax = zeros(1,length(S));
ws = zeros(1,length(S));
Vmax = zeros(1,length(S));
twmaxspeed = zeros(1,length(S));

%Initialize 2 dimensional arrays for plotting.
Clspec = zeros(length(S),JumpSize);
Cdspec = zeros(length(S),JumpSize);
LDspec = zeros(length(S),JumpSize);
Power = zeros(length(S),JumpSize);
```

```
Excess = zeros(length(S),JumpSize);
RC = zeros(length(S),JumpSize);
E = zeros(length(S),JumpSize);
R = zeros(length(S),JumpSize);
tw = zeros(length(S),JumpSize);
v = zeros(length(S),JumpSize);

%% CALCULATIONS:
%Begin for loop. Each loop will calculate all parameters for each wing area
%in the initial array S.
for ii=1:length(S)

%Calculate the stall speed:
Stall_Speed(ii) = sqrt(2*W/(Density*S(ii)*max(1.3518)));

%Create array of velocities:
v(ii,:)  = linspace(Stall_Speed(ii),Stall_Speed(ii)+50,JumpSize);

%Get the required Cl and Cd from drag polar provided fit:
Clspec(ii,:) = 2*W./(Density.*v(ii,:).^2.*S(ii));
Cdspec(ii,:)  = CDmin + k.*(Clspec(ii,:) - CLmin).^2;
LDspec(ii,:) = Clspec(ii,:)./Cdspec(ii,:);

%Get the required power based on speed:
Power(ii,:) =W.*v(ii,:)./(LDspec(ii,:));

%Calculate excess power and rate of climb:
Excess(ii,:) = Pmax-Power(ii,:);
RC(ii,:) = Excess(ii,:)  ./ W;
RCmax(ii) = max(RC(ii,:));

%Calculate endurance for each velocity:
E(ii,:) = Rt.^(1-n)*(ntot.*Volts.*C./(Density.*v(ii,:).^3.*S(ii).*CD0./2+2.*W.^2.*k./(Dens
%Calculate range for each velocity:
R(ii,:) = E(ii,:).*v(ii,:)*3.6;

%Calculate velocity for maximum endurance:
vE(ii) = sqrt((2.*W./(Density.*S(ii))).*sqrt(k./(3*CDmin)));
%Calculate velocity for maximum range:
vR(ii) = sqrt((2.*W./(Density.*S(ii))).*sqrt(k./CDmin));

%Calculate the max endurance:
Emax(ii) = Rt.^(1-n)*(ntot.*Volts.*C./((2./sqrt(Density.*S(ii))).*(CD0.^(1/4)).*((2.*W*sqrt
%= max(E(ii,:));
%Calculate the max range:
Rmax(ii) = (Rt.^(1-n)*((ntot.*Volts.*C)./((1./sqrt(Density.*S(ii))).*(CD0.^(1/4)).*((2.*W*
%= max(R(ii,:));

%Calculate Weight / surface area :
ws(ii) =W/S(ii);

%Find the maximum velocity
 u = find(Power(ii,:)<Pmax+.1 &  Power(ii,:)>Pmax-.1);
Vmax(ii) =  v(ii,u(1));
```

```
%Get thrust over weight:
tw(ii,:) = Pmax ./ v(ii,:);

%Get thrust over weight at the maximum speed:
twmaxspeed(ii) = tw(ii,u(1)) ;

end

%Calculate endurance for different discharge coefficients:
Rs = zeros(1,100);
for jj = 1:100
Rs(jj) = (Rt.^(1-ns(jj))*((ntot.*Volts.*C)./((1./sqrt(Density.*S(ii))).*(CD0^(1/4))*((2.*W
end

%Calculate drag polar for ploting:
coefs=polyfit(alpha(1:13),cl(1:13),1);
line=polyval(coefs,alpha(1:13));

lowest=find(cd==min(cd));
C_dp=cd(lowest)+k*(line-line(lowest)).^2;

vv=18;
C_l_op=W*g/(.5*Density*vv^2*S);
C_d_op=cd(lowest)+k*(C_l_op-line(lowest)).^2;
C_dp2=.026+(cl.^2/(pi*Oswald*AR));

C_d_0=cd(lowest)+k*(0-line(lowest)).^2;

%% Print the information:

fprintf('The wing areas are:')
S
fprintf('The wing loadings are:')
ws
fprintf('The t/w at max speed are:')
twmaxspeed
fprintf('The stall speeds are:')
Stall_Speed
fprintf('The maximum speeds are:')
Vmax
fprintf('The maximum endurances are:')
Emax
fprintf('The speed for maximum endurances are:')
vE
fprintf('The maximum ranges are:')
Rmax
fprintf('The speed for maximum ranges are:')
vR
fprintf('The maximum rates of climb are:')
RCmax

%% Plot:

%Create legend:
Leg=cell(length(S),1);
```

```
for pl1 = 1:length(S)
Leg{pl1} =strcat('Wing area =  ', num2str(S(pl1)),'  [m^2]');
end

%LIFT COEFFICIENT VS ALPHA
figure
plot(alpha,cl,'-x','LineWidth',1.1)
title('Coefficient of Lift')
xlabel('Angle of attack (deg)')
ylabel('C_L')
hold on
plot(alpha(1:13),line,'r','LineWidth',1.1)
grid on
legend('Experimental Data', 'Line of Best Fit')

figure
plot(alpha,cl./cd,'x-','LineWidth',1.1)
title('Lift to Drag Ratio')
xlabel('Angle of attack (deg)')
ylabel('C_l/C_d')
grid on

figure
plot(cl(1:12),cd(1:12),'x-','LineWidth',1.1)
title('Drag Polar')
xlabel('C_L')
ylabel('C_D')
xlim([0 1])
hold on
plot(cl(1:12),C_dp(1:12),'--','LineWidth',1.1)
plot(cl(1:12),C_dp2(1:12),'--','LineWidth',1.1)
plot(C_l_op,C_d_op,'go','LineWidth',1.2)
plot(0,C_d_0,'ro','LineWidth',1.2)
legend('Experimental','Theoretical Using C_D min','Theoretical Using C_D at 0 Lift','Opera
grid on


% DRAGG COEFFICIENT VS ALPHA
figure
plot(alpha, cd,'-x')
title('Drag coefficient vs Angle of attack')
xlabel('Angle of attack [Degrees]');
grid on
 set(findall(gca, 'Type', 'Line'),'LineWidth',1.2);
ylabel('Cd');


%RATE OF CLIMB VS VELOCITY
figure
hold on
grid on
for pl1 = 1:length(S)
plot(v(pl1,:),RC(pl1,:))
end
legend(Leg)
```

```
title('Rate of climb vs Velocity')
xlabel('Velocity [m/s]');
ylabel('Rate of climb [m/s]');
 set(findall(gca, 'Type', 'Line'),'LineWidth',1.2);
hold off

% %RANGE VS DISCHARGE PARAMETER
figure
hold on
grid on
plot(ns,Rs)
title('Maximum Range vs Discharge parameter')
xlabel('Discharge parameter');
ylabel('Range [Km]');
 set(findall(gca, 'Type', 'Line'),'LineWidth',1.2);
hold off

%ENDURANCE VS VELOCITY
figure
hold on
grid on
for pl1 = 1:length(S)
plot(v(pl1,:),E(pl1,:))
end
legend(Leg)
title('Endurance vs Velocity')
xlabel('Velocity [m/s]');
ylabel('Endurance [h]');
 set(findall(gca, 'Type', 'Line'),'LineWidth',1.2);
hold off
%
%RANGE VS VELOCITY
figure
hold on
grid on
for pl1 = 1:length(S)
plot(v(pl1,:),R(pl1,:))
end
legend(Leg)
title('Range vs Velocity')
xlabel('Velocity [m/s]');
ylabel('Range [km]');
 set(findall(gca, 'Type', 'Line'),'LineWidth',1.2);
hold off


%POWERS VS VELOCITY
figure
hold on
grid on
for pl1 = 1:length(S)
plot(v(pl1,:),Power(pl1,:))
end
plot(v(1,:),Pmax*ones(1,length(v)))
Leg{length(S)+1} =strcat('Power available [w]');
```

```
legend(Leg)
title('Power required and available vs Velocity')
xlabel('Velocity [m/s]');
ylabel('Power [w]');
 set(findall(gca, 'Type', 'Line'),'LineWidth',1.2);
hold off
```