Blade Element Momentum Theory (BEMT) Manual

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BEMT Install and Startup

To use the program, the BEMT folder must be downloaded from: https://github.com/raalf/BEMT.
The full program is self contained in the single folder. Open the folder In MATLAB and navigate to "BEMT Module" folder by following the path:

BEMT-master → BEMT Module

The "BEMT Module" folder should contain the following folders, scripts and functions:

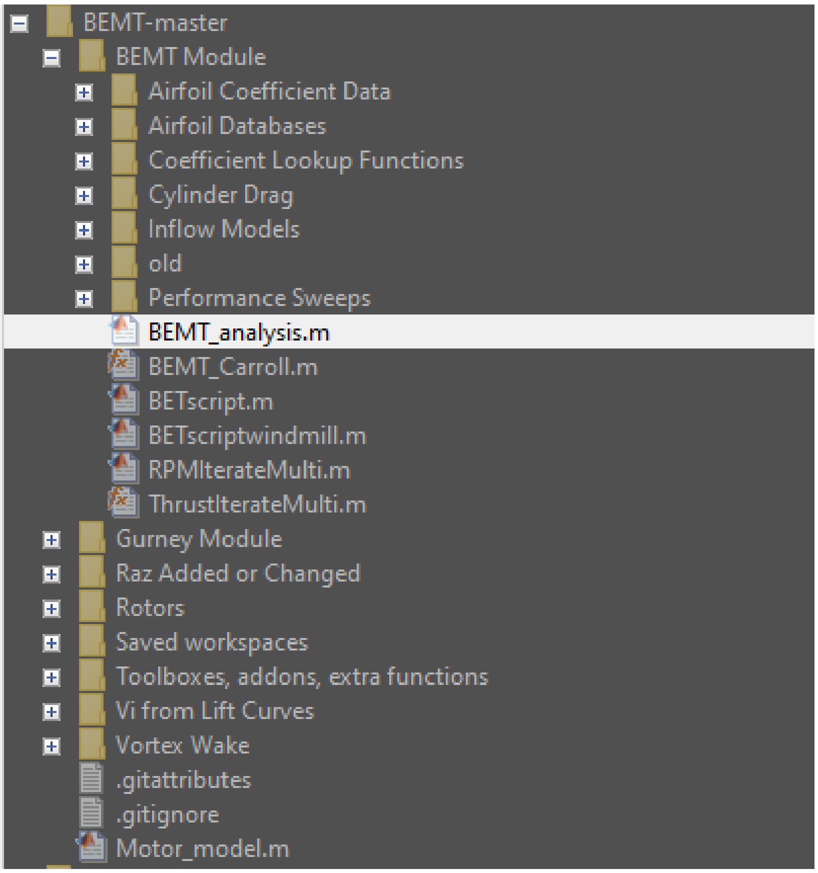


Figure 1: BEMT Folder Tree

To access the analysis code, open "BEMT_analysis.m" from the tree on the left side.

Breakdown of Code

The program contains six sections that need to be filled out with the required parameters.

Section 1: Analysis Type and Save Workspace

```
21    %% [1] ANALYSIS TYPE AND SAVE WORKSPACE:
22    % ----------------------------------------
23        % Save workspace
24 -      options.save_workspace              =   'off';        % on/off toggle to save workspace each time BEMT_Carroll is called (i.e. in performance sweeps)
25 -      options.saved_workspace_identifier  =   'Testing';    % identifier for saved workspace structure, string
26
27        %  ANALYSIS TYPES
28        %       1   -   INPUT -> Shaft Speed  / CALC -> Thrust, etc
29        %       2   -   INPUT -> Thrust       / ITER CALC -> Shaft Speed, etc
30        %       3   -   INPUT -> PERFORMANCE SWEEPS
31 -      options.analysistype =   3;
32
33            % ANALYSIS TYPE 1 -> SHAFT SPEED KNOWN
34                % Input RPM in [3a]
35
36            % ANALYSIS TYPE 2 -> THRUST KNOWN
37 -              oper.Treq       =   5.4;                 % Required Thrust [N]
38 -              oper.accuracy   =   0.5;                 % Thrust Allowable Percent Error
39
40            % ANALYSIS TYPE 3 -> PERFORMANCE SWEEPS
41            %       1   -   Velocity [m/s]
42            %       2   -   Advance Ratio [Dimensionless]
43            %       3   -   Shaft speed [RPM]
44            %       4   -   Angle of attack [deg]
45 -              options.sweep_type =   2;
46 -              options.sweep_range     =   [0 0.1 1];            % Start value ; Step size; End value
47
```

Figure 2: Section 1

Save Workspace

- Line 24: [string] on/off toggle to save workspace each time BEMT_Carroll is called (i.e. in performance sweeps). BEMT_Carroll is the function that performs the calculations and is called each time the code is run.
- Line 25: [string] Identifier for saved workspace structure (can input any string)

Analysis Types

- Line 31: [value] Select which analysis type to run from the options given in Lines 28-30.

This program contains three different analysis types:

1. The rotor shaft speed is inputted and the various performance parameters (thrust, power, forces, moments etc.) are calculated and outputted.
2. The required thrust is inputted, and the shaft speed is iteratively calculated and outputted.
3. Performance sweep. One of either velocity, advance ratio, shaft speed, or angle of attack can be swept through while all other parameters are held constant.

Analysis Type 2 → Thrust Known

- Line 37: [value] Required thrust in [N]
- Line 38: [value] Thrust allowable percent error in [%]

Analysis Type 3 → Performance Sweeps

- Line 45: [value] Select what parameter is to be swept through from the options given in Lines 41-44.
- Line 46: [value] Specify the start value, step size, and end value for the performance sweep

4 different parameters can be swept through, while keeping all other parameters constant:

1. Velocity [m/s]
2. Advance Ratio [Dimensionless]
3. Shaft Speed [RPM]
4. Angle of Attack [deg]

Section 2: Flow Field Information

```
48     %% [2] FLOW FIELD INFORMATION:
49     % ----------------------------
50 -          flow.rho               =   1.225;            % Air density [kg/m^3]
51 -          flow.mu                =   1.8*10^(-5);      % Dynamic viscosity [kg/m s]
52 -          flow.V                 =   0;                % Freestream velocity [m/s]
53 -          flow.inflow_angle      =   0;               % Rotor AoA [deg]. Angle between freestream and rotor plane (0 to +/- 90).
54                                                          % (Edgewise flight = 0 [deg], Propeller mode = 90 [deg])
55
```

Figure 3: Section 2

- Line 50: [value] Air density in [kg/m^3]
- Line 51: [value] Dynamic viscosity in [kg/m*s]
- Line 52: [value] Freestream velocity in [m/s]
- Line 53: [value] Inflow angle. The inflow angle is the angle between the freestream and the rotor plane. The inflow angle should be set to 0 degrees for fully edgewise flow and set to 90 degrees for propeller analysis.

Section 3a: Rotor Geometry, Operating Parameters and Coefficient Options

```
56    %% [3a] ROTOR GEOMETRY, OPERATING PARAMETERS AND COEFFICIENT OPTIONS:
57    % ----------------------------------------------
58        % Rotor .dat file
59          % use file name string to link to file saved in rotor folder
60          rotor.name            =   'T_motor';
61
62        % Rotor rotational speed [RPM] (For analysis types 1 and 3)
63          oper.rpm              =   1436;
64
65         % for multiple rotor configs, modify individual rotor rpm's as needed eg:   % oper.rpm_multi = [2000 2000 2010 2010]
66
67
68        % Inflow method
69          oper.inflow_type      =   1;
70                                                    % 1 = Uniform momentum w/ linear inflow model: Edgewise velocity component, forward flight. (default for FF)
71                                                    % 2 = Graded momentum: Small angle assumption / no swirl / linear lift curve slope (only used for axial flow and hover)
72                                                    % 3 = Graded momentum: Small angle assumption / no swirl / coeffs look-ups + stall model (only used for axial flow and hover)
73                                                    % 4 = Graded momentum: Large angles / with swirl (only used for axial flow and hover)
74                                                    % 5 = Potential flow: Vortex tube with constant momentum assumption for single rotor wake structure
75
76                                                    % Default is 1: Uniform momentum theory as it handles most flight states that can be determined with momentum theory
77                                                    % 2-4 are more advanced radially graded forumlations (hover and axial flight only).
78                                                    % Code reverts back to 1 for forward flight states.
79                                                    % 5 is vortex theory approach for the rotor wake (verified but not validated vs experiments)
80
81        % Number of azimuth positions             % Number of blade azimuth positions [Integer]. First it at 0 or 2pi rad.
82          oper.azimuth_num      =   8;
83
84        % Induced velocity toggle                 % BEMT/BET toggle 'on' (BEMT), 'off' (BET, so vi = 0). Induced velocity component of inflow
85          oper.toggle_vi        =   'on';
86
87        % Viscous effects toggle and options      % Viscous effects toggle: 'on' or 'off' (c_d = 0)
88          oper.toggle_visc      =   'on';
89          oper.alpha_zero       =   -0.03;          % If viscous effects are off, include also a zero lift angle estimate [rad]
90          oper.a_0              =   2*pi;           % Lift curve slope [1/rad]
91
92        % Aerodynamic coefficients options        % To save computation time, airfoil data can be pre-computed.
93                                                    % Coeefs are queried instead of interpolated for each AoA.
94                                                    % 'on' database is pre-computed but first checks to see if database exists with same resolution.
95                                                    % 'off' data is interpolated for each exact AoA and station
96                                                    % ('opt' special case for optimizations)
97                                                    % Database naming % convention: '<airfoilname>_<AoAresolution>'
98          options.toggle_precompute   =   'on';
99          options.AoAresolution       =   0.5;      % Database resolution for angle of attack, [deg].
100         options.REresolution        =   10000;    % Database resolution for Reynolds number.
101         options.RErange_max         =   300000;   % Max Reynolds number range. Min is set @ zero. Keep @ ~ 10^6
102         options.toggle_coeff_plot   =   'off';     % Toggle to generate 3D plots for Re vs AoA vs coeff for newly generated dataset
103
```

Figure 4: Section 3a

- Line 60: [string] The file name string of the rotor .mat file that specifies the coordinate geometry of the blade element. This .mat file must be located under the “Rotors” folder as shown in Figure 6.

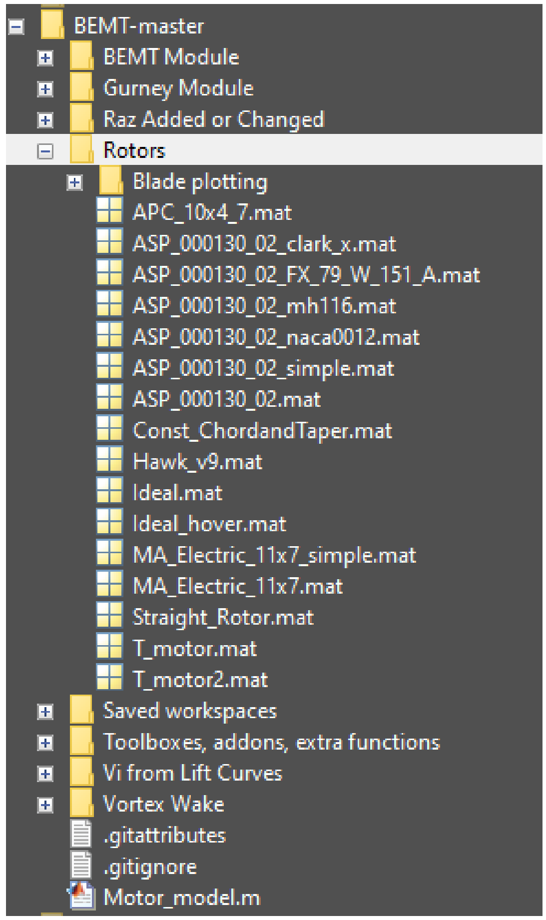


Figure 5: File location of rotor geometry .mat file

- Line 63: [value] The rotor rotational speed in [RPM]. For multi-rotor setups refer to note on Line 65.
- Line 69: [value] Select which inflow type from the options given in Lines 70-74. The analysis method (theory) for the inflow is selected here, based on what type of inflow is approaching the rotor plane.
- Line 82: [value] Number of blade azimuth positions iterated through.
- Line 85: [string] Toggle for induced velocity. 'on' for BEMT analysis, 'off' for BET analysis (V_i=0)

Viscous effects toggle and options

- Line 88: [string] Toggle for viscous effects, 'on' or 'off'
- Line 89: [value] Zero lift angle estimate in [rad]. This value must be specified if viscous effects in Line 88 are 'off'
- Line 90: [value] Lift curve slope [1/rad]

Aerodynamic coefficients options

- Line 98: [string] Toggle to allow airfoil data to be pre-computed and placed into a newly generated database

- Line 99: [value] Database resolution for angle of attack in [deg]
- Line 100: [value] Database resolution for Reynolds number
- Line 101: [value] Max Reynolds number range
- Line 102: [string] Toggle to generate 3D plots for Re vs AoA vs Coeff for newly generated dataset

Section 3b: Rotor Quick Modifiers

```
104 %% [3b] ROTOR QUICK MODIFIERS:
105 % ----------------------------
106       blade.modify_pitch     =   0;              % Collectively add/subtract from pitch [deg]
107       blade.scale_radius     =   0.83333;              % Scale radius by multiplier from original [default = 1]
108
```

Figure 6: Section 3b

- Line 106: [value] Modify blade pitch in [deg]. Can increase or decrease blade pitch (positive and negative values can be inputted)
- Line 107: [value] Scale blade radius by multiplier from original. Default value is 1.

Section 4: Multirotor Analysis Tool: Vehicle Configuration/ Wake Options

```
109 %% [4] MULTIROTOR ANALYSIS TOOL: VEHICLE CONFIGURATION/WAKE OPTIONS:
110 % -----------------------------------------------------------------
111     % Vehicle configuration
112        rotor.num_rotors        =   1;
113        rotor.orientation       =   'square';           % Orientation of rotors: 'diamond' (single rotor leading) or 'square' (Two rotors leading)
114        rotor.armLENGTH         =   0.5;                % Length of arm to UAV geometric center, [m].
115        rotor.roll              =   0;                  % Collective vehicle roll angle along longitudinal x-axis, [deg].
116        rotor.rp_twist          =   0;                  % Twist of rotor support arm, [deg].
117        rotor.rp_cant           =   0;                  % Cant of rotor support arm, [deg].
118
119        %rotor.armLENGTH         =   ((2+.25).*0.2286./2)./(sind(360./rotor.num_rotors./2));
120
121     % Adjacent wake effects toggle
122        oper.toggle_WIM         =    'off';             % WIM Wake interactions on/off.
123
124     % Vortex wake options
125        wake.num_seg            =    32;                % Number of segments in ring element
126        wake.num_elements       =    50;                % Number of ring or helix loop elements
127        wake.type               =    'ring';            % Type of wake elements used (ring or helix)
128
```

Figure 7: Section 4

Vehicle Configuration

- Line 112: [value] Specify number of rotors that are to be analyzed. Line 113 to Line 117 need to be specified if number of rotors is greater than 1.
- Line 113: [string] Orientation of rotors, ‘diamond’ (single rotor leading) or ‘square’ (Two rotors leading)
- Line 114: [value] Length of arm to UAV geometric center in [m]
- Line 115: [value] Collective vehicle roll angle along longitudinal axis in [deg]
- Line 116: [value] Twist of rotor support arm in [deg]
- Line 117: [value] Cant of rotor support arm, [deg]. Cant is defined as a counter clockwise rotation of the entire rotor disk about an orthogonal axis on the vehicle’s xy- plane and passing through vehicle’s center point. (i.e pitch of the rotor arm)

Adjacent Wake Effects Toggle

- Line 122: [string] Toggle for Wake Impingement Model (WIM) Wake interactions.

Vortex Wake Options

- Line 125: [value] Number of segments in vortex ring element
- Line 126: [value] Number of ring or helix loop elements
- Line 127: [string] Type of wake elements used (‘ring’ or ‘helix’)

Section 5: High Lift Devices

```
129     %% [5] HIGH LIFT DEVICES:
130     % ----------------------
131         % Load Gurney Flap Conditions
132         % See separate Gurney_Setup.m for additional options
133 -         oper.gurney             =    0;                  % 1 for ON, 0 for OFF
134
```

Figure 8: Section 5

Section 5 is where high lift devices such as Gurney flaps can be specified. This section only contains the toggle for including Gurney flaps in the analysis. To specify Gurney flap options, refer to Gurney_Setup.m, located under the Gurney Module folder (Figure 9).

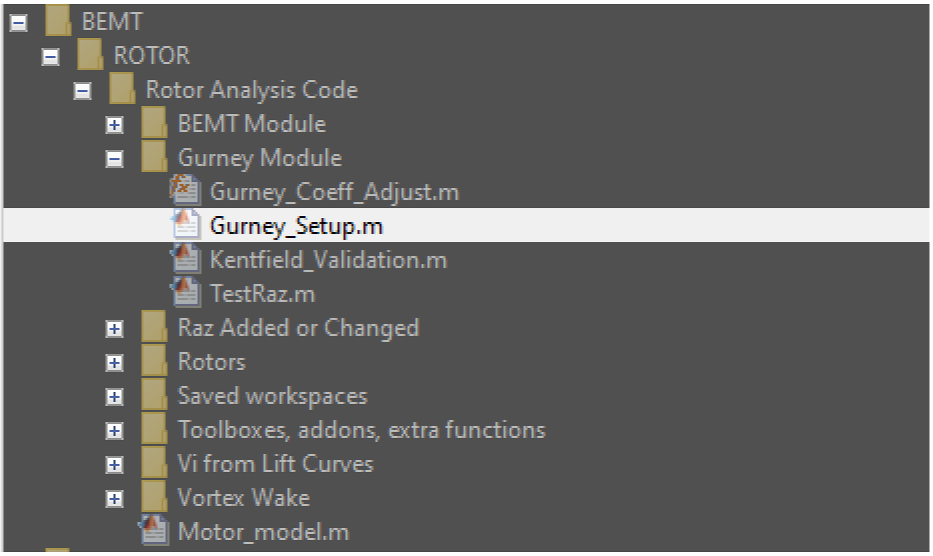


Figure 9: File Location for 'Gurney_Setup.m'

- Line 133: [value] Toggle for loading Gurney Flap conditions (1 for ON, 0 for OFF)

Once the parameters are set in BEMT_analysis.m Sections 1-6, run the program and click “add to path” at prompt.

Output

Depending on the type of analysis chosen the program will run anywhere from a few seconds to a few minutes.

The calculations are output in a structure called “perf”, that will be located in the ‘Workspace’ window (Figure 10).

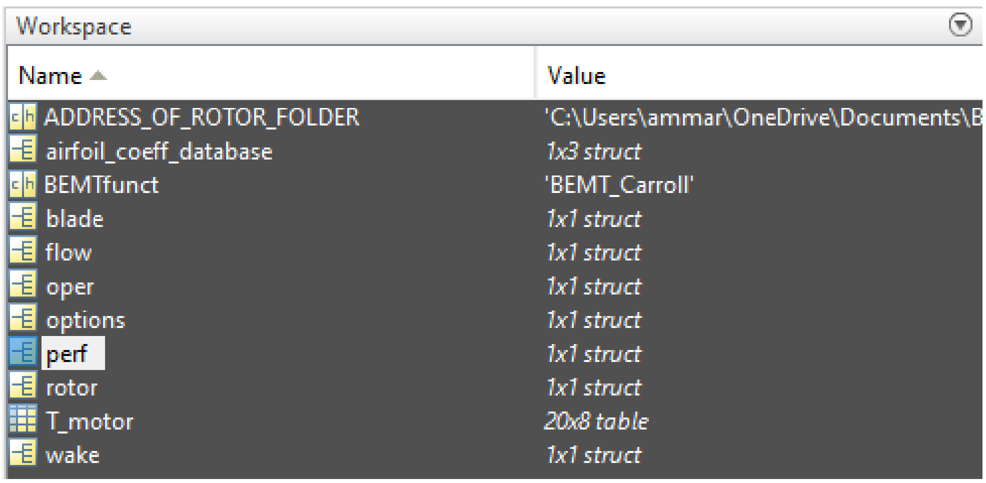


Figure 10: Output files

If a performance sweep (Option 3) is run then the calculations are output in a structure called “perf_sweep”, which will also be located in the ‘Workspace’ window (Figure 11).

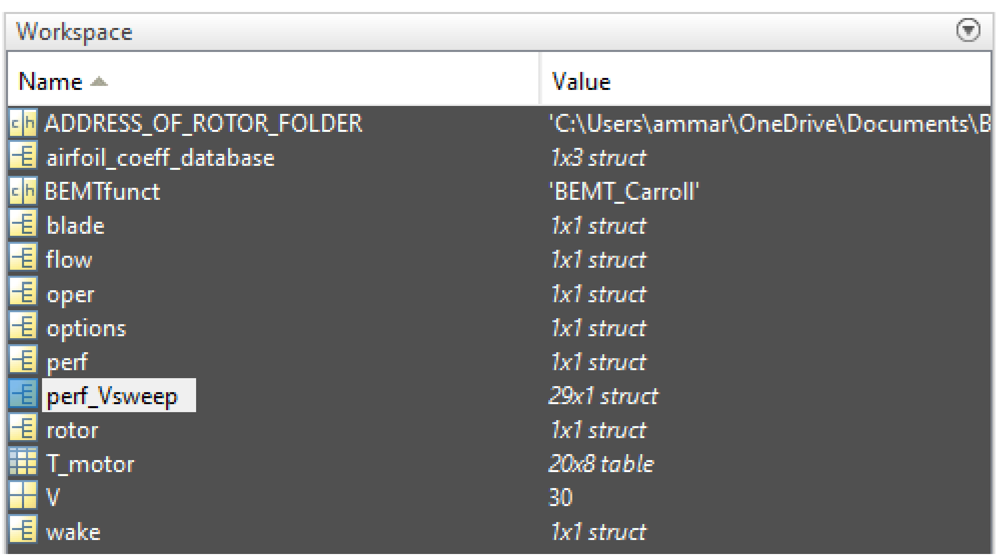
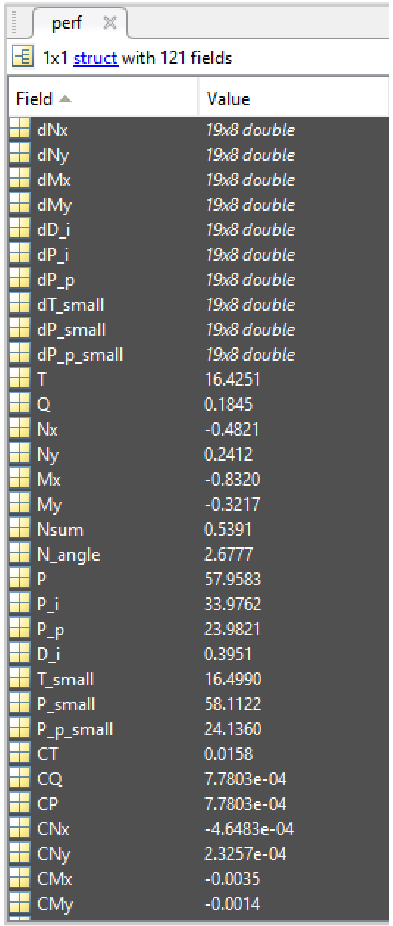


Figure 11: Output files for Performance Sweep



perf

1x1 struct with 121 fields

Field	Value
dNx	19x8 double
dNy	19x8 double
dMx	19x8 double
dMy	19x8 double
dD_i	19x8 double
dP_i	19x8 double
dP_p	19x8 double
dT_small	19x8 double
dP_small	19x8 double
dP_p_small	19x8 double
T	16.4251
Q	0.1845
Nx	-0.4821
Ny	0.2412
Mx	-0.8320
My	-0.3217
Nsum	0.5391
N_angle	2.6777
P	57.9583
P_i	33.9762
P_p	23.9821
D_i	0.3951
T_small	16.4990
P_small	58.1122
P_p_small	24.1360
CT	0.0158
CQ	7.7803e-04
CP	7.7803e-04
CNx	-4.6483e-04
CNy	2.3257e-04
CMx	-0.0035
CMy	-0.0014

Figure 12: Portion of sample output from the "perf" structure

The output “perf” structure contains a magnitude of data about the analysis. This includes but is not limited to the output forces, moments and coefficients. The “perf” structure also contains the variables inputted in to the analysis in addition to the blade and airfoil data. For every iteration it also contains the incremental forces and moments at the blade stations for every azimuth location. A portion of a sample output “perf” structure is shown in Figure 12.

perf_Vsweep

21x1 struct with 121 fields

Fields	P_p	D_i	T_small	P_small	P_p_small	CT	CQ	CP	CNx	CNy	CMx	CMy	CT_sigma
1	12.6753	0.7214	11.9816	77.2939	12.8241	0.0114	0.0010	0.0010	5.3517e-20	-5.3517e-20	0	-5.8527e-19	0.1293
2	12.6826	0.7198	11.9943	77.1502	12.8322	0.0114	0.0010	0.0010	-2.0654e-05	5.5798e-06	-1.0858e-04	-2.2448e-04	0.1294
3	12.6332	0.7145	12.0234	76.5732	12.7799	0.0115	0.0010	0.0010	-4.3001e-05	1.4184e-05	-2.0609e-04	-3.9582e-04	0.1298
4	12.6532	0.7069	12.0831	75.8630	12.7991	0.0115	0.0010	0.0010	-6.7835e-05	2.3512e-05	-3.4189e-04	-6.0345e-04	0.1304
5	12.7351	0.6964	12.1448	74.8023	12.8803	0.0116	0.0010	0.0010	-8.8423e-05	3.5702e-05	-4.5972e-04	-7.7688e-04	0.1311
6	12.9569	0.6820	12.2203	73.5556	13.1018	0.0117	9.8547e-04	9.8547e-04	-1.1083e-04	4.4422e-05	-5.9423e-04	-9.5581e-04	0.1320
7	13.2393	0.6697	12.3453	72.5860	13.3831	0.0118	9.7247e-04	9.7247e-04	-1.2760e-04	5.9605e-05	-7.0187e-04	-0.0011	0.1334
8	13.6736	0.6518	12.4398	71.1159	13.8162	0.0119	9.5275e-04	9.5275e-04	-1.4967e-04	6.7520e-05	-8.2313e-04	-0.0012	0.1345
9	14.1370	0.6348	12.5701	69.8450	14.2785	0.0120	9.3570e-04	9.3570e-04	-1.6771e-04	7.8244e-05	-9.4898e-04	-0.0013	0.1359
10	14.5872	0.6181	12.7169	68.6199	14.7271	0.0121	9.1928e-04	9.1928e-04	-1.8578e-04	9.2904e-05	-0.0011	-0.0014	0.1376
11	15.1086	0.6060	12.9423	67.8944	15.2475	0.0124	9.0955e-04	9.0955e-04	-2.0021e-04	1.0461e-04	-0.0012	-0.0015	0.1401
12	15.5474	0.5918	13.1384	66.9355	15.6845	0.0126	8.9671e-04	8.9671e-04	-2.1366e-04	1.2163e-04	-0.0013	-0.0016	0.1422
13	16.1966	0.5776	13.4106	66.2253	16.3316	0.0128	8.8720e-04	8.8720e-04	-2.3199e-04	1.3612e-04	-0.0014	-0.0016	0.1452
14	16.6419	0.5616	13.5467	65.1550	16.7759	0.0130	8.7284e-04	8.7284e-04	-2.4417e-04	1.5010e-04	-0.0015	-0.0016	0.1468
15	17.2559	0.5479	13.7598	64.4698	17.3895	0.0132	8.6365e-04	8.6365e-04	-2.6073e-04	1.5984e-04	-0.0017	-0.0017	0.1491
16	17.7098	0.5347	13.9586	63.7164	17.8419	0.0134	8.5356e-04	8.5356e-04	-2.7149e-04	1.7302e-04	-0.0018	-0.0017	0.1513
17	18.2129	0.5185	14.1266	62.7997	18.3445	0.0135	8.4126e-04	8.4126e-04	-2.8708e-04	1.8282e-04	-0.0019	-0.0017	0.1532
18	18.6862	0.5097	14.3787	62.4304	18.8174	0.0138	8.3631e-04	8.3631e-04	-2.9954e-04	1.9143e-04	-0.0020	-0.0017	0.1560
19	19.1600	0.4961	14.5479	61.6666	19.2890	0.0139	8.2608e-04	8.2608e-04	-3.1511e-04	1.9830e-04	-0.0021	-0.0017	0.1579
20	19.5796	0.4842	14.7104	61.0251	19.7080	0.0141	8.1748e-04	8.1748e-04	-3.3074e-04	2.0620e-04	-0.0023	-0.0017	0.1597
21	20.0565	0.4735	14.8980	60.5741	20.1853	0.0143	8.1142e-04	8.1142e-04	-3.4000e-04	2.1272e-04	-0.0024	-0.0017	0.1617
22													
23													
24													
25													
26													

Figure 13: Portion of sample output from the "perf_Vsweep" structure

The output “perf_Vsweep” structure contains the same information as the “perf” structure for every step in the sweep. A portion of a sample output “perf_Vsweep” structure is shown in Figure 13.

Appendix

Comparison to Experimental Data

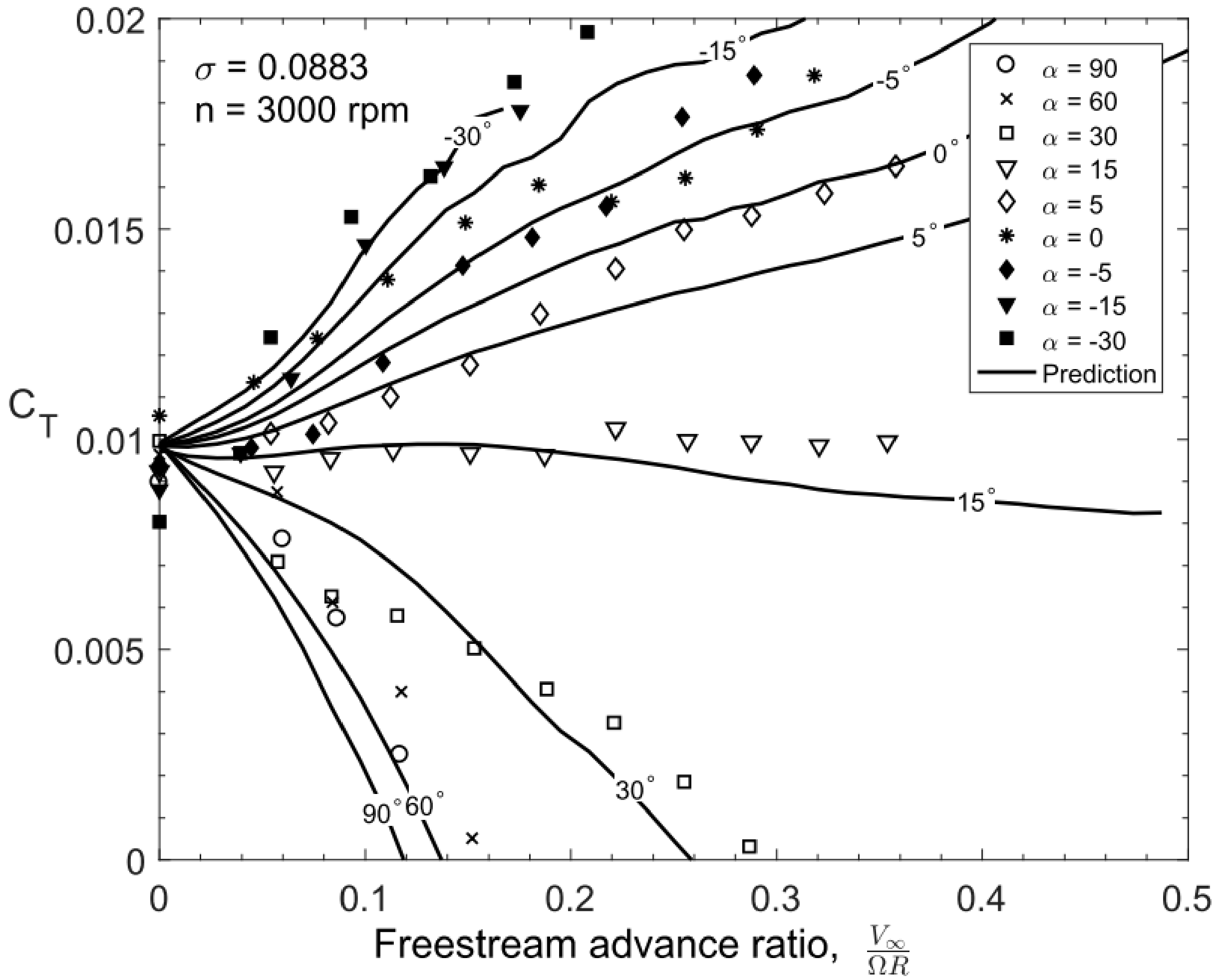


Figure 14: Predicted and Experimental Data for CT vs. Freestream Advance Ratio for a range of inflow angles.

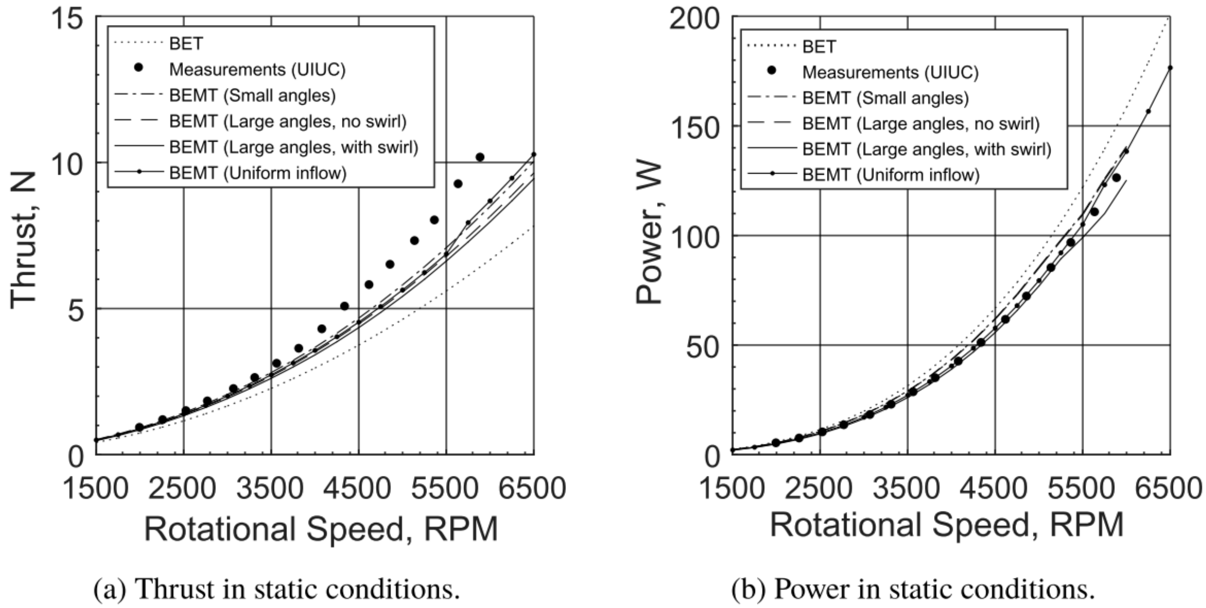


Figure 15: Predicted and Experimental results for thrust and power at static conditions for a range of RPMs.

References

Carroll, Tim B. "A DESIGN METHODOLOGY FOR ROTORS OF SMALL MULTIROTOR VEHICLES." Ryerson University, 2014.