Numerical Analysis of Cyclorotor Aerodynamic Properties in Hovering State

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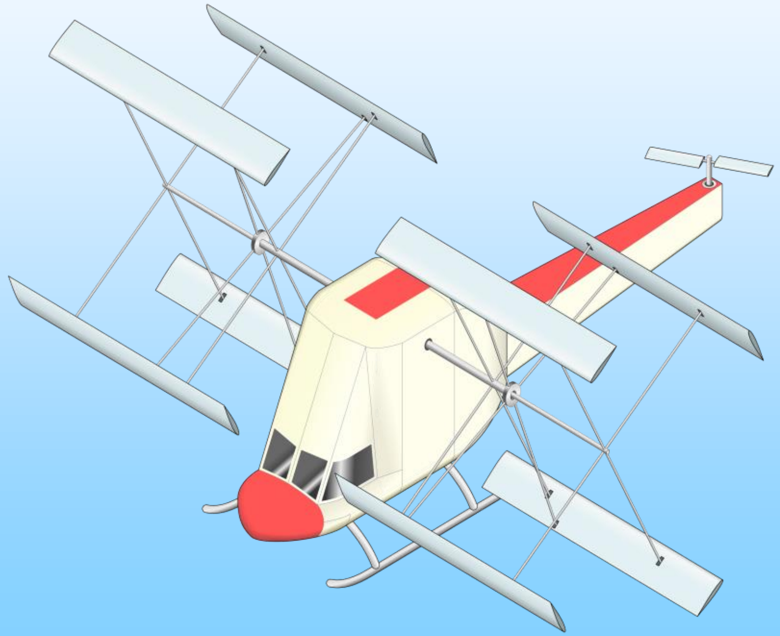
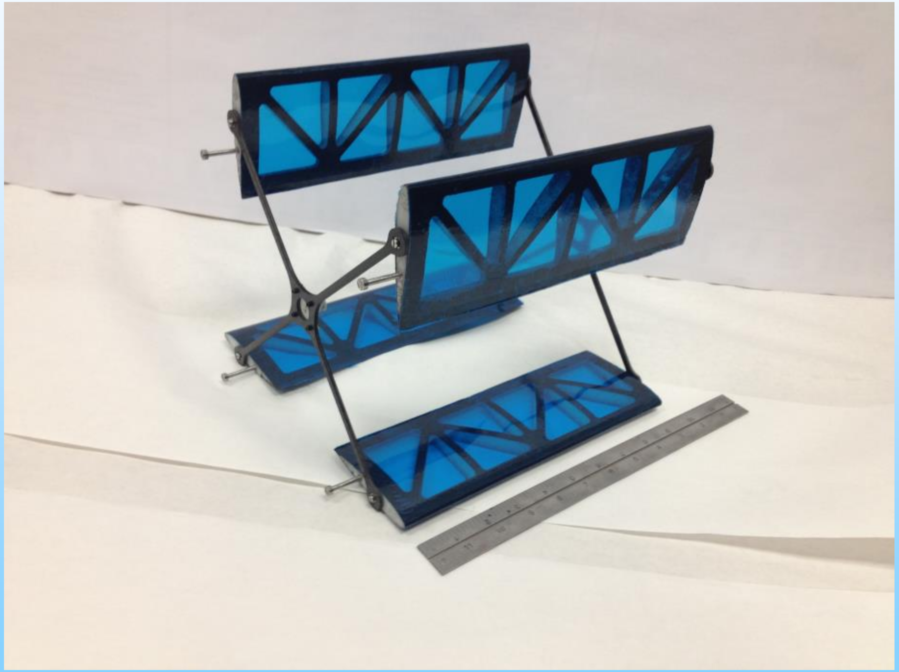
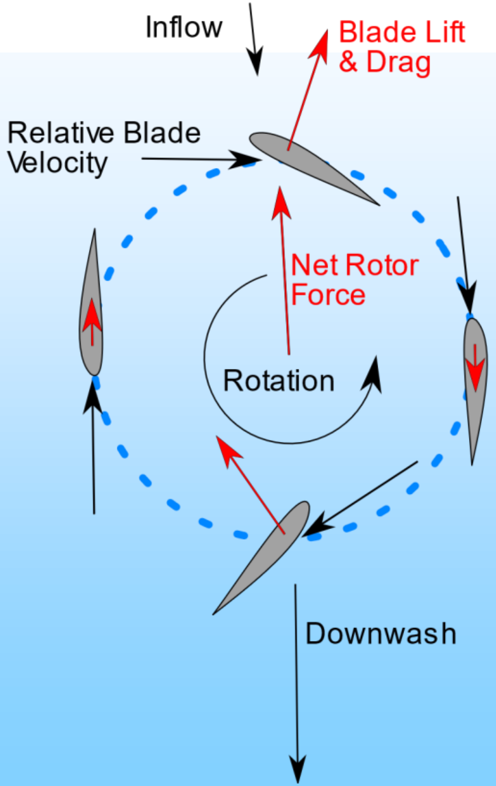


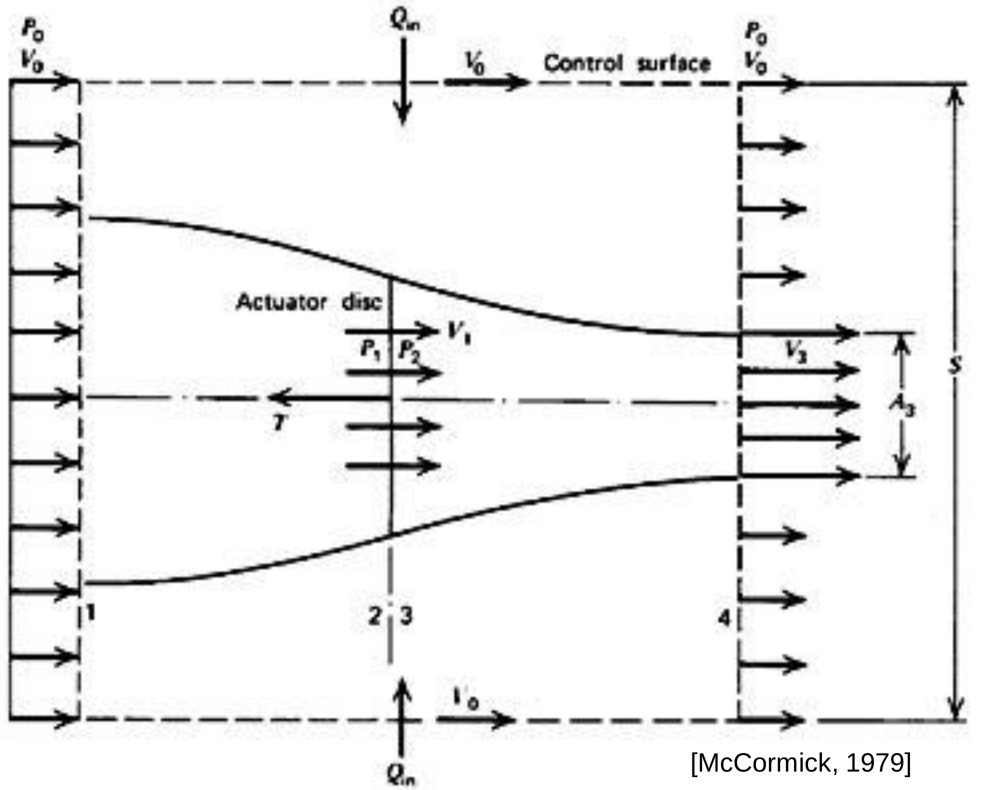
Introduction



[Zachary Adams, 2013]



Preliminaries



[McCormick, 1979]

$$T = \int_S \rho V(\vec{V} \cdot \vec{n})\, dA$$

$$T = -(\rho_0 V_0 A_0)V_0 + (\rho_3 V_3 A_3)V_3$$

$$T = \dot{m}(V_3 - V_0)$$

Preliminaries

$$\mathrm{T} = \dot{m}(V_3 - V_0)$$

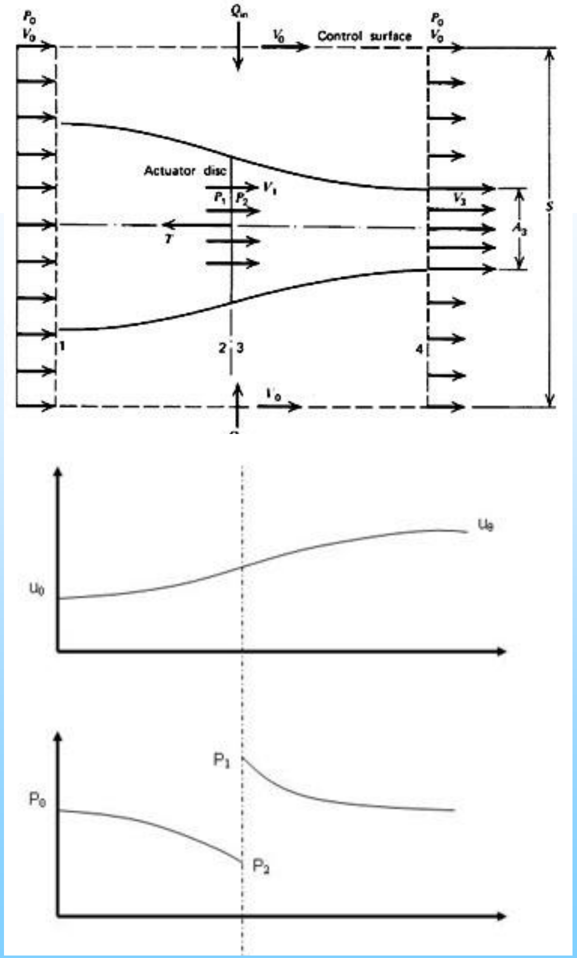
$$P = T \cdot V_{disk} = \underline{\dot{m}(V_3 - V_0)}V_{disk}$$

$$P = \frac{1}{2}\dot{m}(V_3)^2 - \frac{1}{2}\dot{m}(V_0)^2 = \underline{\dot{m}(V_3 - V_0)}\frac{V_3 + V_0}{2}$$

$$V_{disk} = \frac{V_3 + V_0}{2}$$

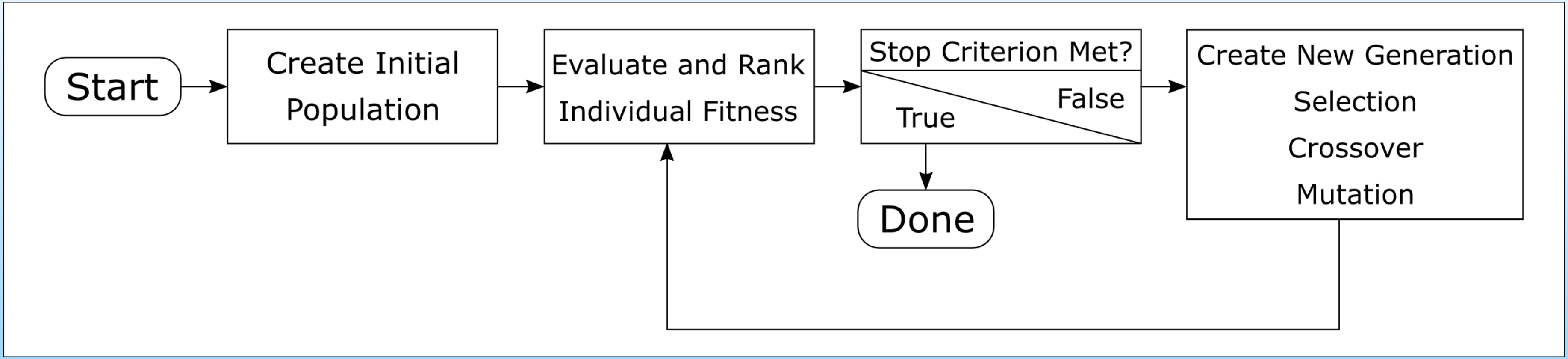
$$\rho\frac{{V_i}^2}{2} + p_i = const.$$

$$T = \frac{1}{2}\rho A(V_3 + V_0)(V_3 - V_0) = \frac{1}{2}\rho A\left({V_3}^2 - {V_0}^2\right)$$

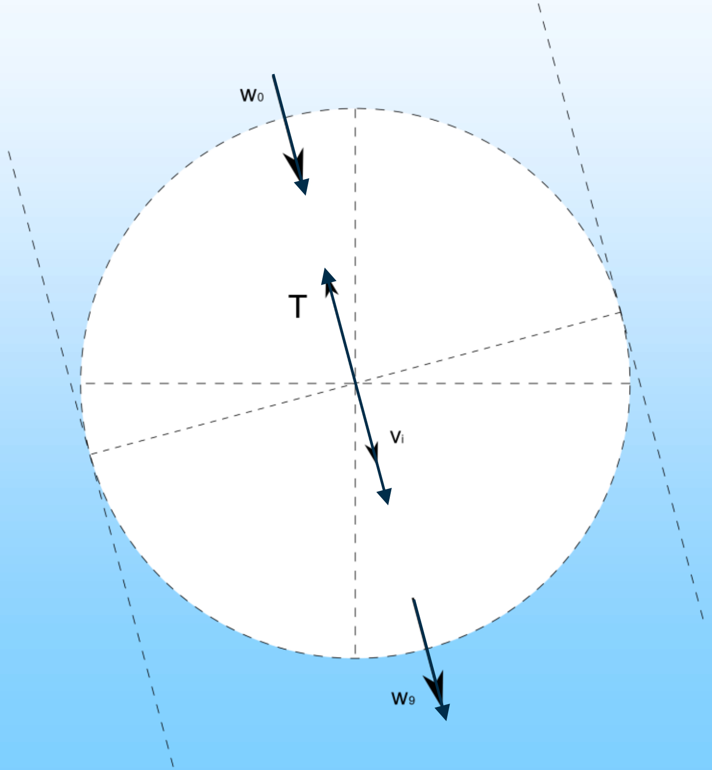


[Kerrebrock, 1980]

Preliminaries



Analytic Model



$$T = A(p_2 - p_1)$$

$$p_2 - p_1 = \frac{1}{2}\rho({w_9}^2 - {w_0}^2)$$

$$T = 2\rho A(w_0 + \Delta w)\Delta w$$

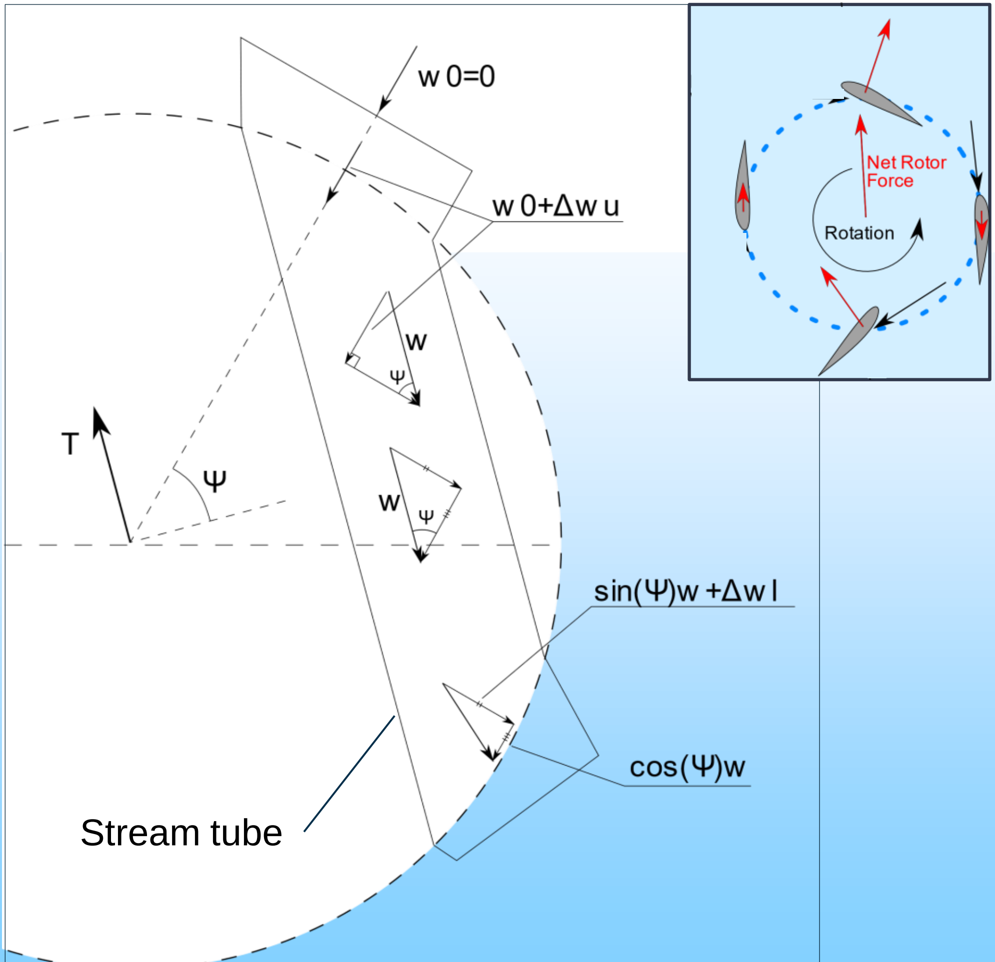
$$\Delta w = \sqrt{\frac{T}{2\rho A}}$$

Analytic Model

$$w = \frac{w_0 + 2\Delta w_u}{\sin(\Psi)} \overset{hov.}{\Longrightarrow} \frac{2\Delta w_u}{\sin(\Psi)}$$

$$T_u = \frac{1}{2}\rho A(w^2 - {w_0}^2) \overset{hov.}{\Longrightarrow} \Delta w_u = \sqrt{\frac{T_u \sin(\Psi)^2}{2\rho A}}$$

$$T_l = 2\rho A \Delta w_l \sqrt{w^2 + 2w\Delta w_l \sin(\Psi) + {\Delta w_l}^2}$$



[Adapted from Moble Benedict, 2010]

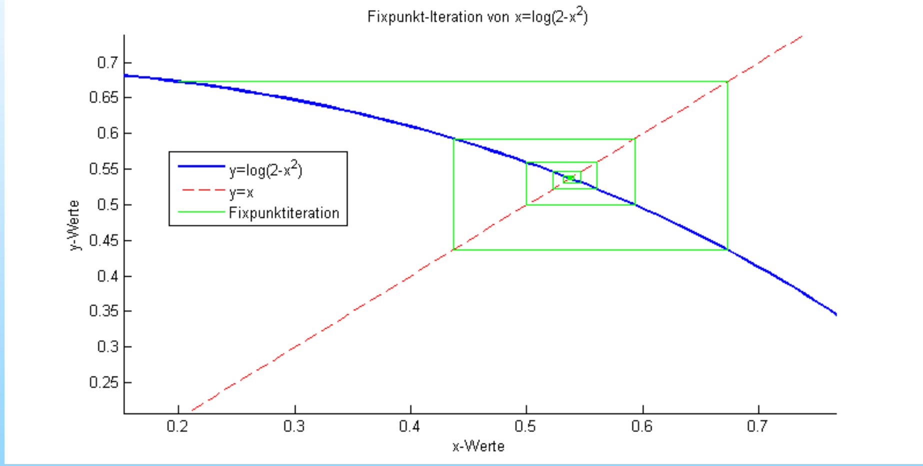
Numerical Root Finding

Fixed-point Iteration

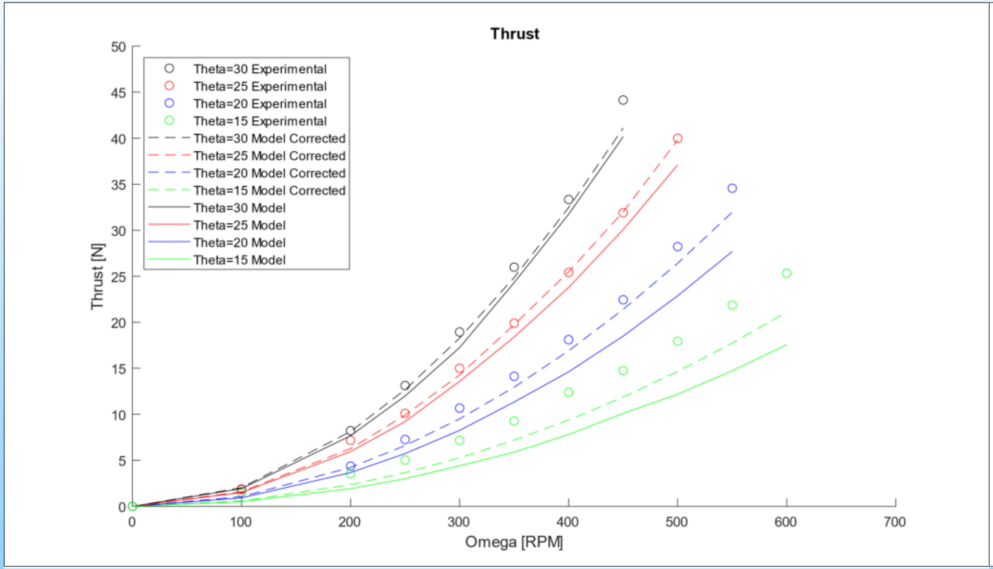
$$T_u(\Delta w) = f_1(\Delta w) = 2\rho A(\Delta w)^2(\sin\psi)^2$$

$$T_u(\Delta w) = f_2(\Delta w, \omega, R, c,)$$

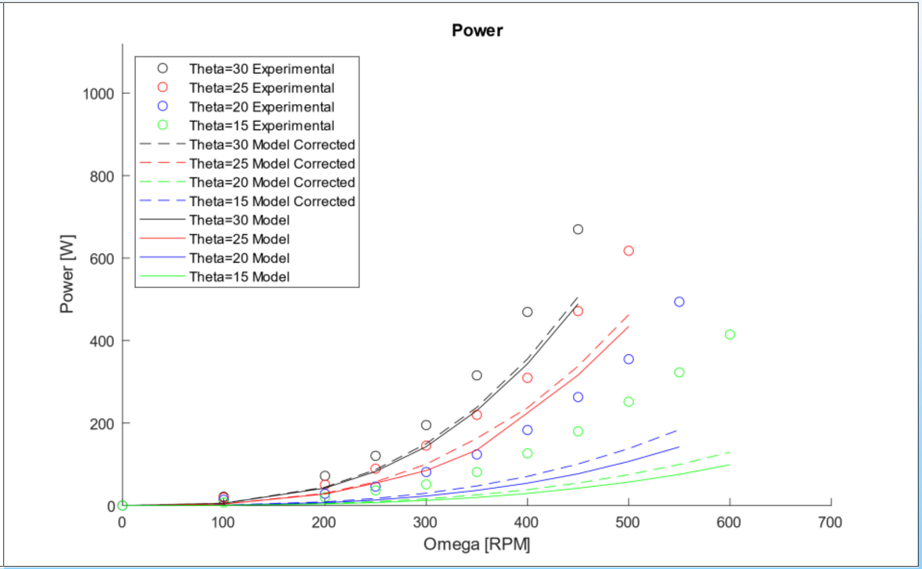
$$\Delta w^{k+1} = \Delta w^k + \left(f_1^{-1}\left(T\left(\Delta w^k\right)\right) - \Delta w^k\right)\alpha_T$$



Validation

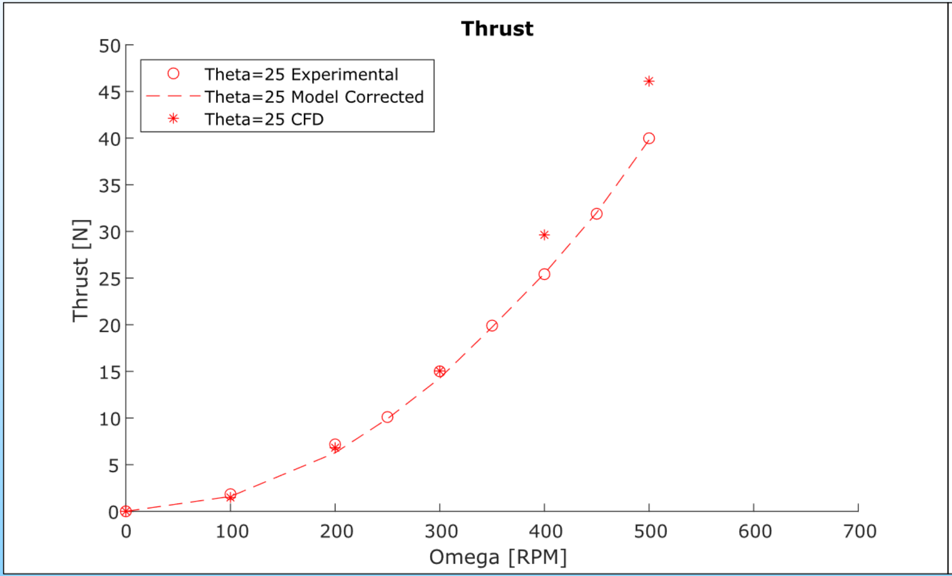


Thrust
Theta=30 Experimental
Theta=25 Experimental
Theta=20 Experimental
Theta=15 Experimental
Theta=30 Model Corrected
Theta=25 Model Corrected
Theta=20 Model Corrected
Theta=15 Model Corrected
Theta=30 Model
Theta=25 Model
Theta=20 Model
Theta=15 Model
Thrust [N]
0
5
10
15
20
25
30
35
40
45
50
0
100
200
300
400
500
600
700
Omega [RPM]

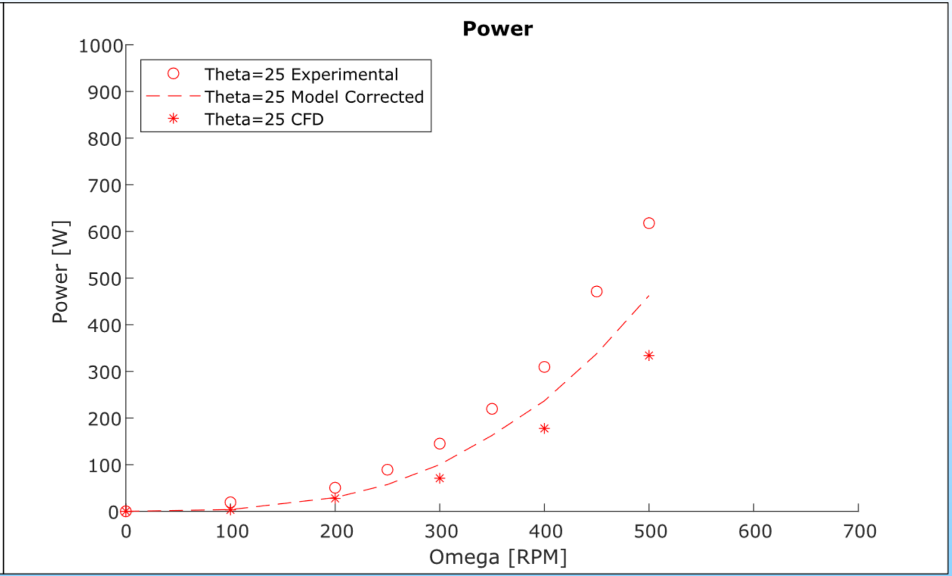


Power
Theta=30 Experimental
Theta=25 Experimental
Theta=20 Experimental
Theta=15 Experimental
Theta=30 Model Corrected
Theta=25 Model Corrected
Theta=20 Model Corrected
Theta=15 Model Corrected
Theta=30 Model
Theta=25 Model
Theta=20 Model
Theta=15 Model
Power [W]
0
200
400
600
800
1000
0
100
200
300
400
500
600
700
Omega [RPM]

Validation

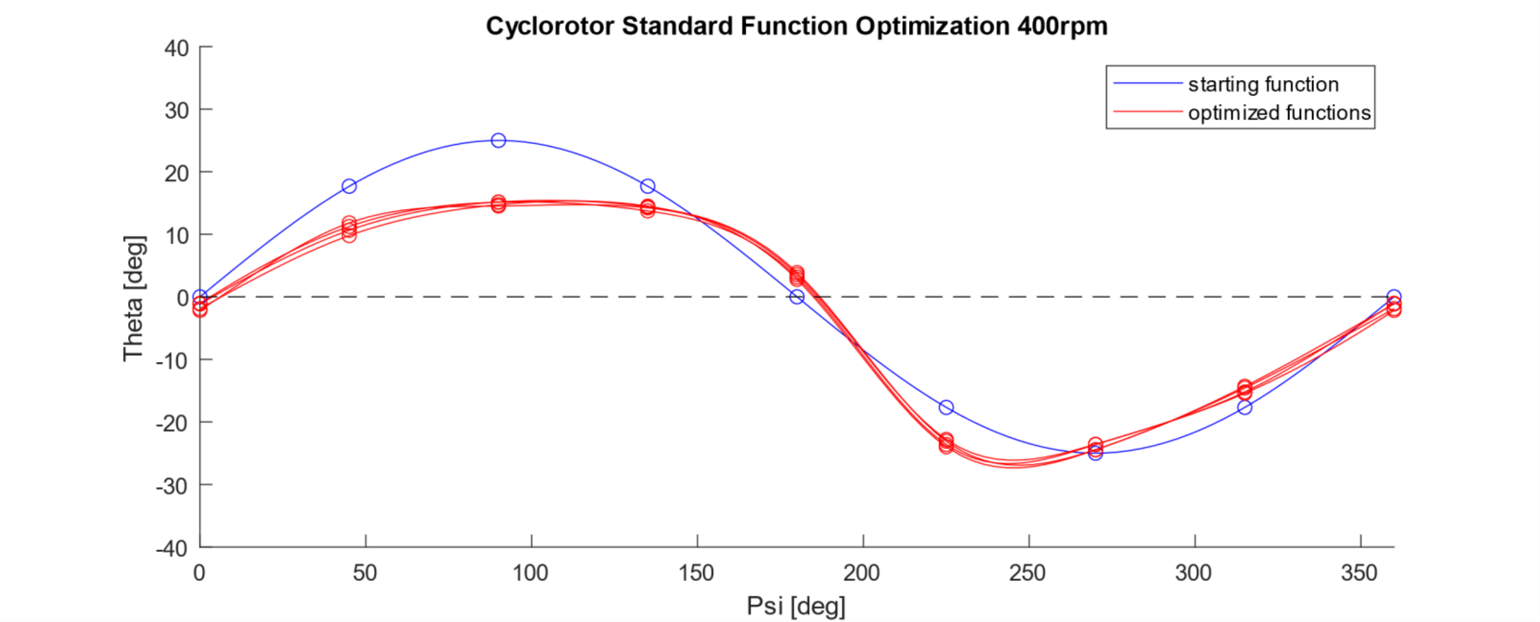


Thrust
Theta=25 Experimental
Theta=25 Model Corrected
Theta=25 CFD
Thrust [N]
Omega [RPM]
0
5
10
15
20
25
30
35
40
45
50
0
100
200
300
400
500
600
700

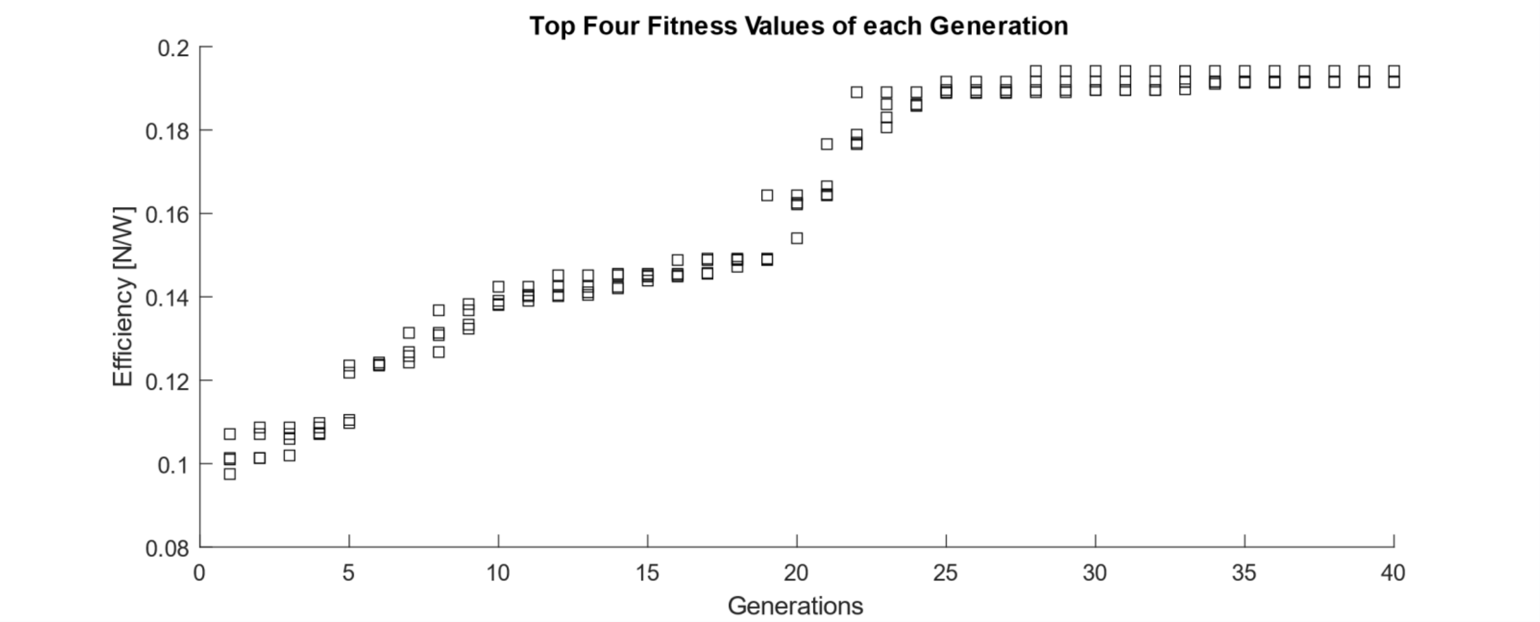


Power
Theta=25 Experimental
Theta=25 Model Corrected
Theta=25 CFD
Power [W]
Omega [RPM]
0
100
200
300
400
500
600
700
800
900
1000
0
100
200
300
400
500
600
700

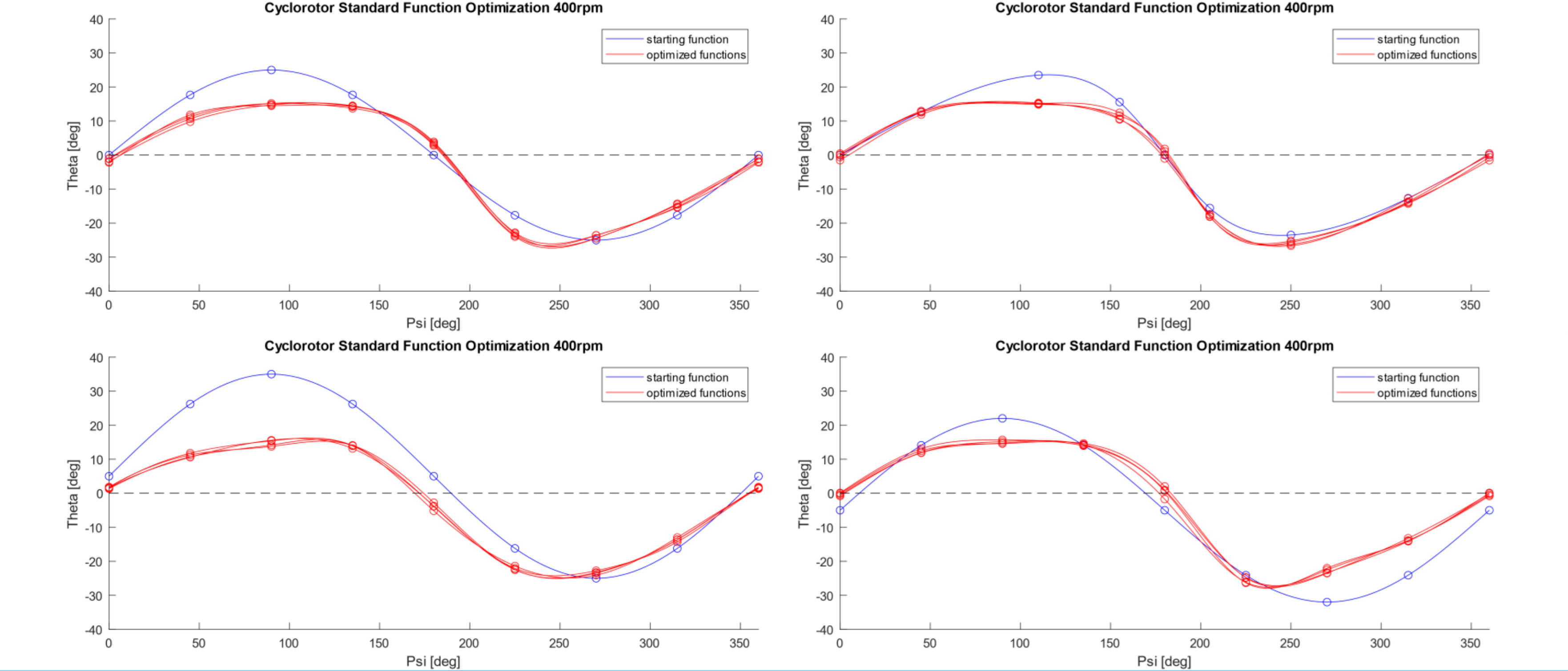
Optimization



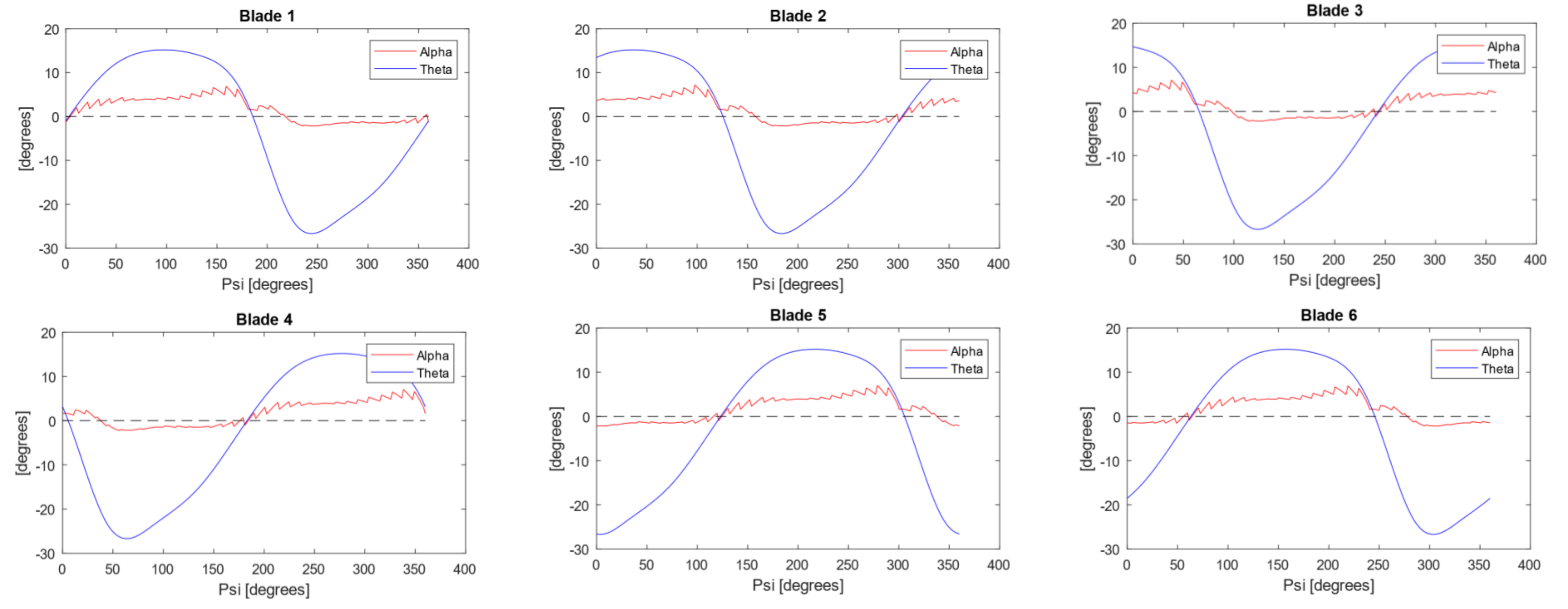
Optimization



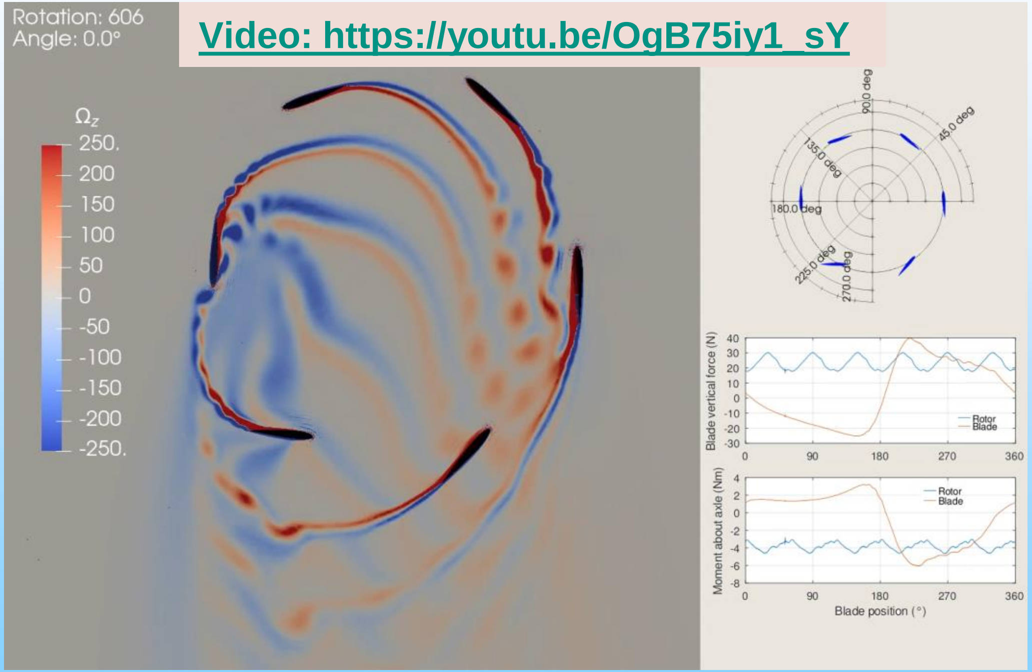
Optimization

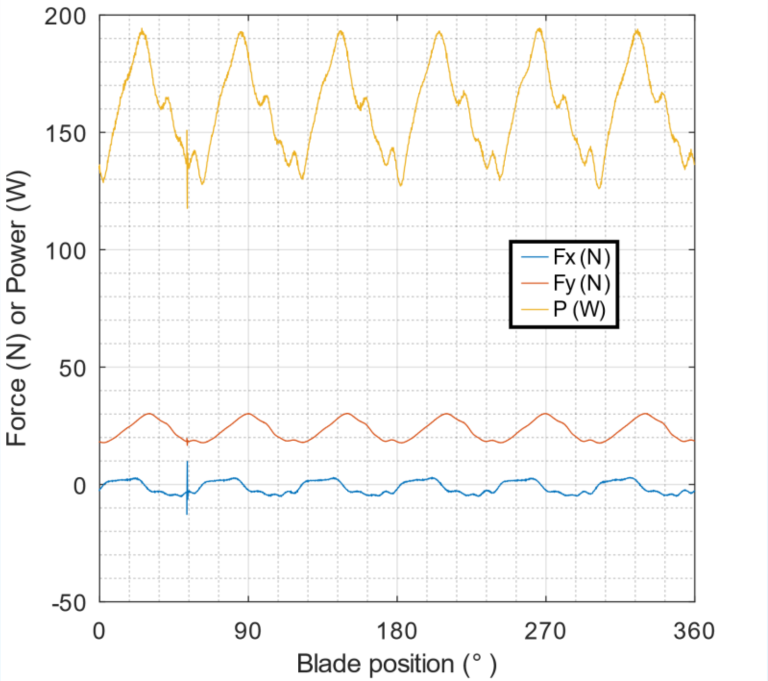


Optimization



Optimization





Conclusions

- Analytic model programmed using actuator disks in series
- Analytic equations solved with iterative methods
- Analytic model is validated using CFD and experimental results
- Genetic algorithm converged onto an optimal function with increased efficiency

Sources

- Aeroelastic Analysis of a MAV-Scale Cycloidal Rotor, Moble Benedict, 2010
- B.W. Aerodynamics, Aeronautics, and Flight Mechanics, McCormick, 1979
- A Performance Prediction Model Using Multiple Streamtubes, H. Strickland, 1975
- Unknown, Kerrebrock, 1980
- Design, Development, and Flight Test of a Small-Scale Cyclogyro UAV Utilizing a Novel Cam-Based Passive Blade Pitching Mechanism, Zachary Adams, 2013

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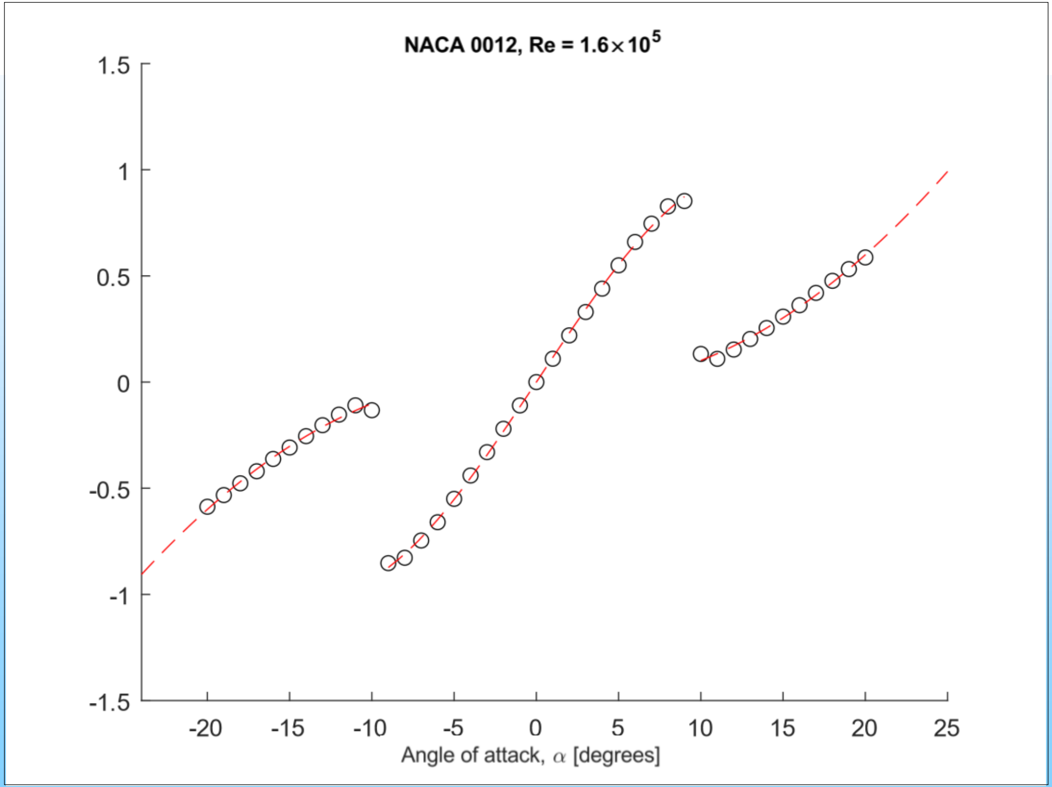
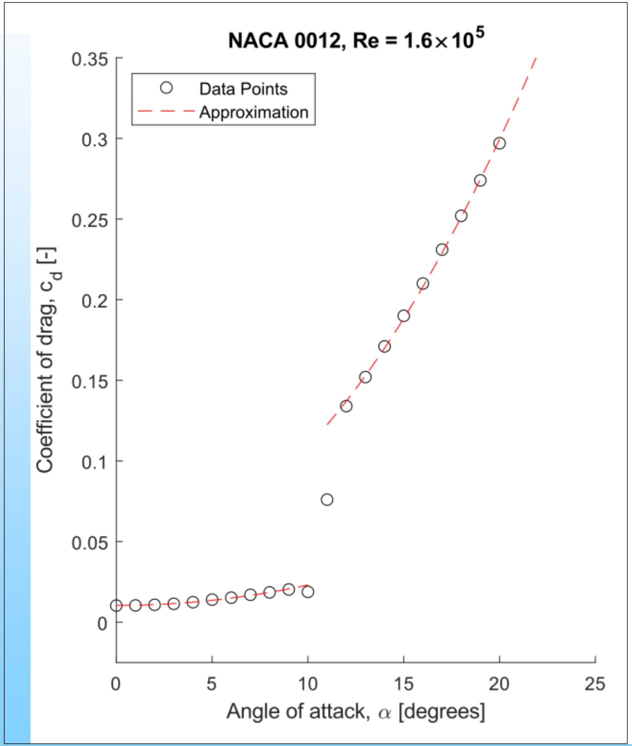
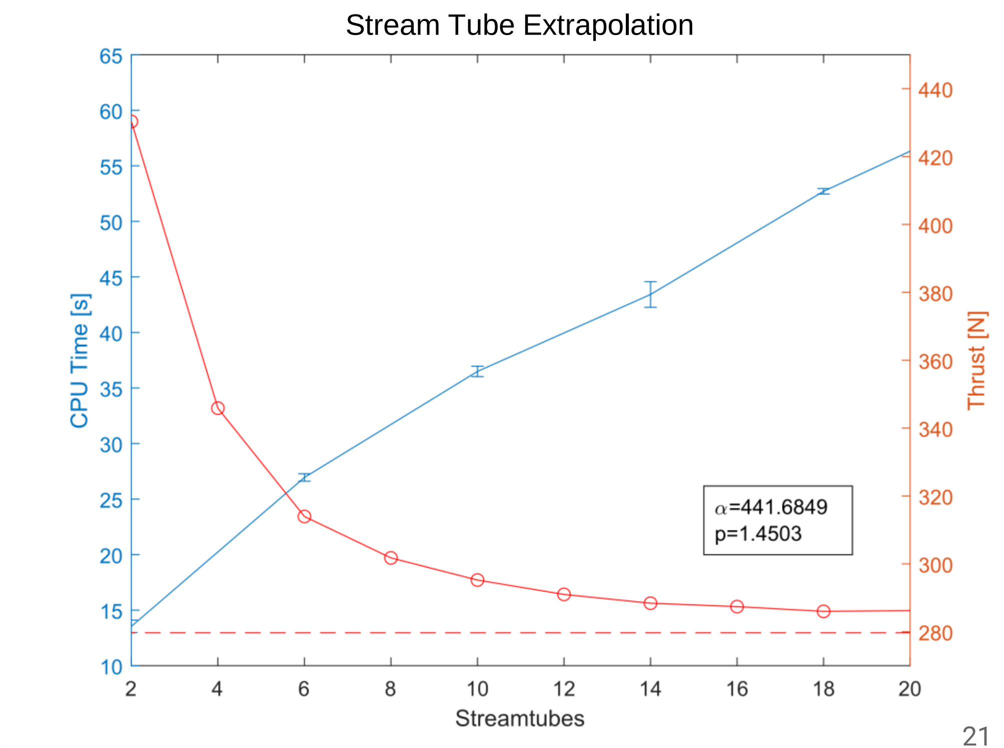

NACA 0012, Re = 1.6×10^5
1.5
1
0.5
0
-0.5
-1
-1.5
-20
-15
-10
-5
0
5
10
15
20
25
Angle of attack, α [degrees]


NACA 0012, Re = 1.6×10^5
Data Points
Approximation
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Coefficient of drag, c_d [-]
0
5
10
15
20
25
Angle of attack, α [degrees]

Computational Optimization

$$\epsilon = T_0 - T_h = \alpha h^p$$

Stream Tubes	Extrapolated	20	14	8	2
Thrust	282	286.221	288.4107	301.7567	430.3303
CPU Time	∞	58.2071	43.418	31.9454	13.5391
Thrust % error	0.00%	1.50%	2.27%	7.01%	52.60%



Genetic Algorithm