Prandtl Propeller Modeling and Evaluation

CONNOR LEMMON

CODE 520/RA-AERODYNAMICS AND PROPULSION

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Overview

- About Me
- Defined Tasks
- Background
- Prandtl Inspired Prop
    - Methods
    - Results
- Previous Prandtl Prop
    - Methods
    - Results
- Conclusions
- Future Work for the Project
- Internship Experience and Personal Future Plans

Connor Lemmon

University of the Pacific

Mechanical Engineering

Incoming 4th Year

Previous Work:

- Mount Hermon - Lead Lifeguard
- Camp Hammer – Apostle Leader

Other Projects:

- Unidirectional Carbon Fiber Orientation Analysis
- Puerto Rico Aid Project

Organizations:

- Theta Chi
- Powell Scholars

Original Tasks

Modeling

- Improve “DesigningPrandtlProp.m” MATLAB code
- Further determine how a Prandtl Prop is created/designed
- Create models of new modified propellers
- Obtain performance data of propellers from XRotor
- Create performance data graphs

Evaluation

- Create testing procedures for models
- Evaluate test data
- Compare results with reported results

Accomplished Tasks

Modeling

- Improve "DesigningPrandtlProp.m" MATLAB code
- Further determine how a Prandtl Prop is created/designed
- Create models of new modified propellers
- Obtain performance data of propellers from XRotor
- Create performance data graphs

Evaluation

- Create testing procedures for models
- Verify existing claims
- Find possible explanations of existing test result data
- Explore possible solutions to undocumented problems

Background – Blade Element Theory (BET)

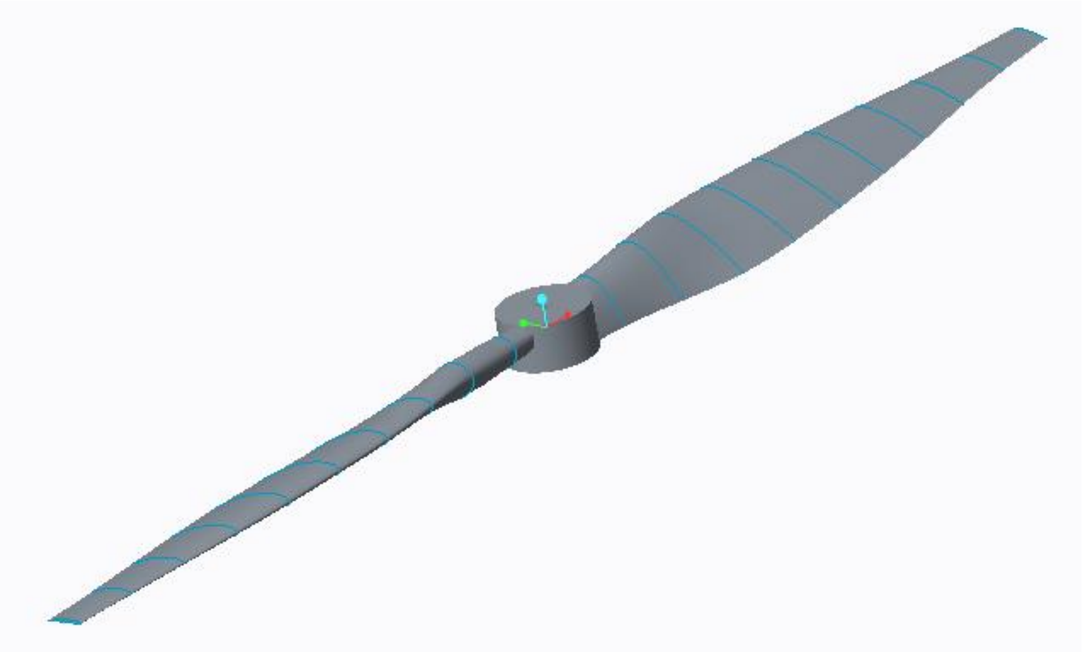
- Common analysis method for propellers, turbines, and fans
- Divides blade into small number of blade sections and calculates values for each section
- More accurate than momentum theory, which treats the propeller as an actuator disk

Background – Minimum Induced Loss (MIL)

- Current design philosophy for propellers
- Seeks to optimize globally by optimizing each section locally
- Finds the lowest value for $\frac{C_d}{C_l}$ at all blade sections
- Induces the lowest amount of drag and torque for high thrust

Background

- Designs exist for both a Prandtl Prop and a Prandtl Fan
- Existing Fan tests have few data points
- No quantitative test data for Prandtl Prop
- Matlab code to convert prop in early stages
- Binder of previous materials and findings



Recovered Prandtl Prop SolidWorks Model

Methods - Equations

Key Blade Element equations:

- $C_y = C_l \cos\phi - C_d \sin\phi$
- $C_x = C_l \sin\phi + C_d \cos\phi$
- $K = \dfrac{C_y}{4\,(\sin\phi)^2}$
- $K' = \dfrac{C_x}{4\cos\phi\sin\phi}$

- $a = \dfrac{\sigma K}{F - \sigma K}$
- $a' = \dfrac{\sigma K'}{F + \sigma K'}$
- $\sigma = \dfrac{Bc}{2\pi r}$
- $\phi = \tan^{-1}\dfrac{v(1+a)}{\Omega r(1-a')}$

So, a is mostly driven by Lift and a' is driven by Drag

Methods - Equations

Loading equations:

- $dT = 2F\rho * v * a(1 + a) * v * 2\pi r * dr$
- $dQ = 2F\rho * v * a'(1 + a) * \Omega r^2 * 2\pi r * dr$
- $dP = \mathrm{d}Q * \Omega$

So lift most heavily contributes to thrust, but it also contributes to torque

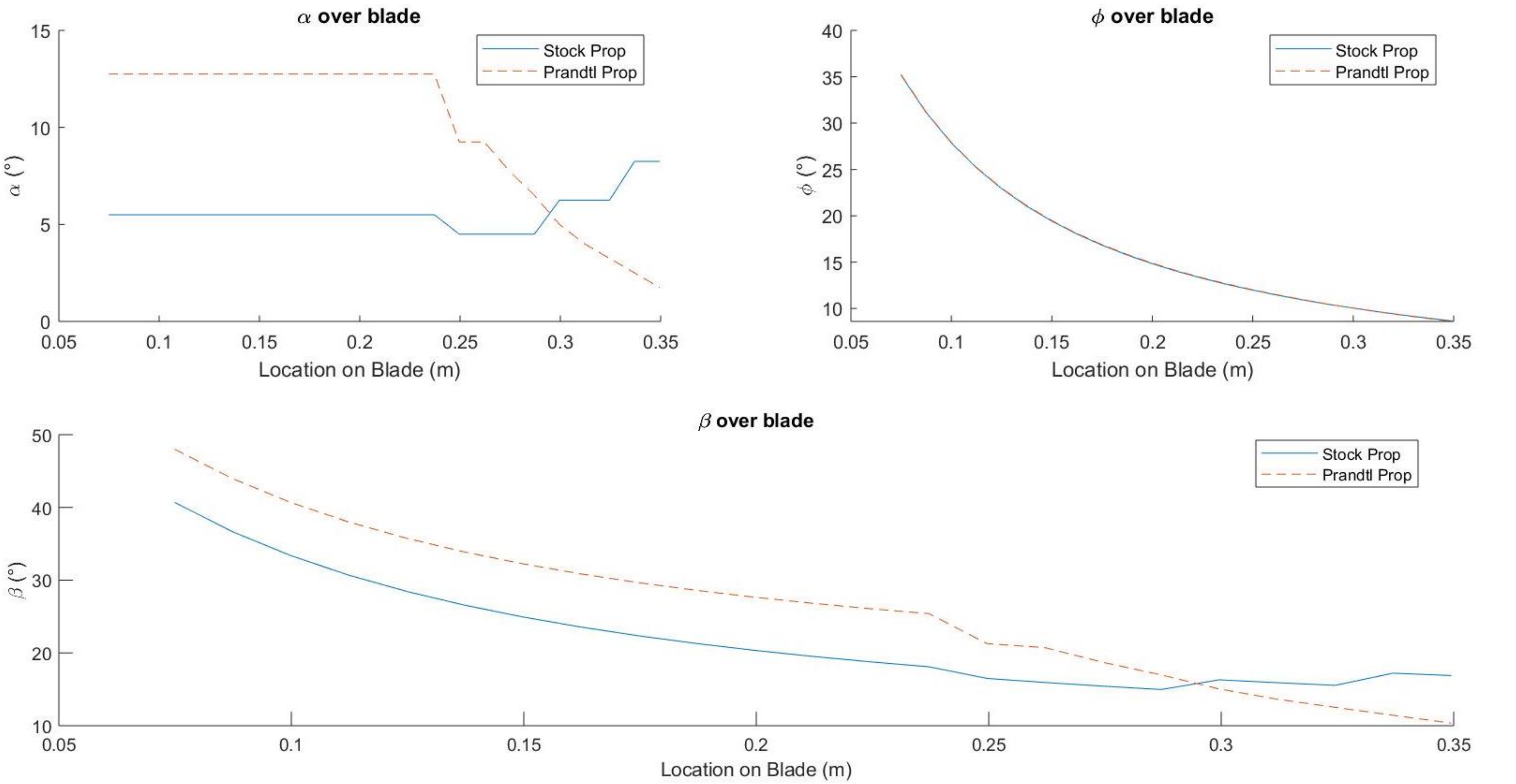
Key Takeaways from Equations

- To increase Thrust, we must increase Lift
- Increasing Lift means that Torque will also increase
  - Therefore, the best way to lower torque seems to be to lower drag
  - As MIL yields the lowest possible drag at each station, the new approach must increase Lift closer to the center of the blade so drag at the tip can be reduced

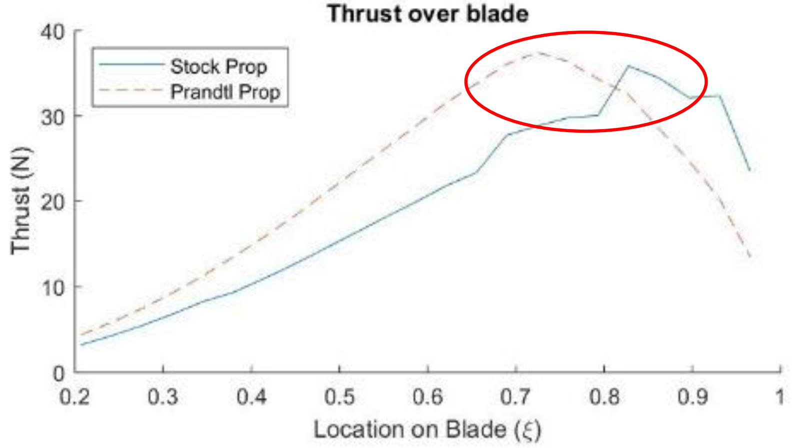
Design Philosophy for Prandtl Inspired Propeller (PIP)

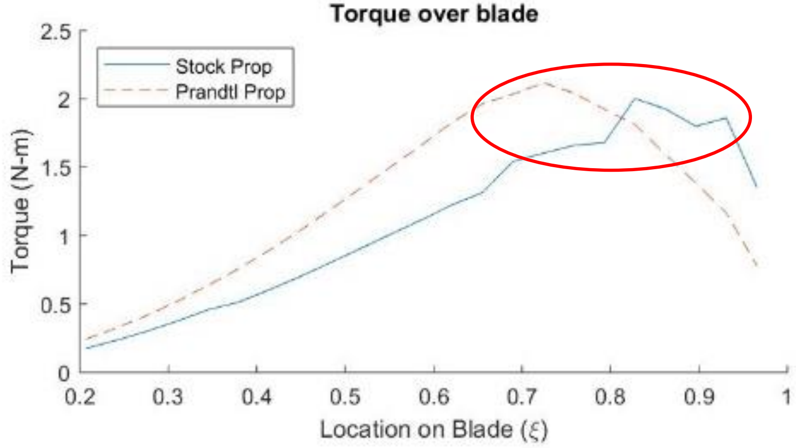
- High C_l for most of the prop, then taper off to lower C_l near the tip
  - Taper is not optimized, currently using linear taper
  - Optimized result expected to be 4^{th} degree based on PRANDTL-D data
- Uses 3 airfoils across blade taken from previous estimates
  - Not properly blended, so there are abrupt changes on in performance at for each new section
  - Same airfoils as stock propeller

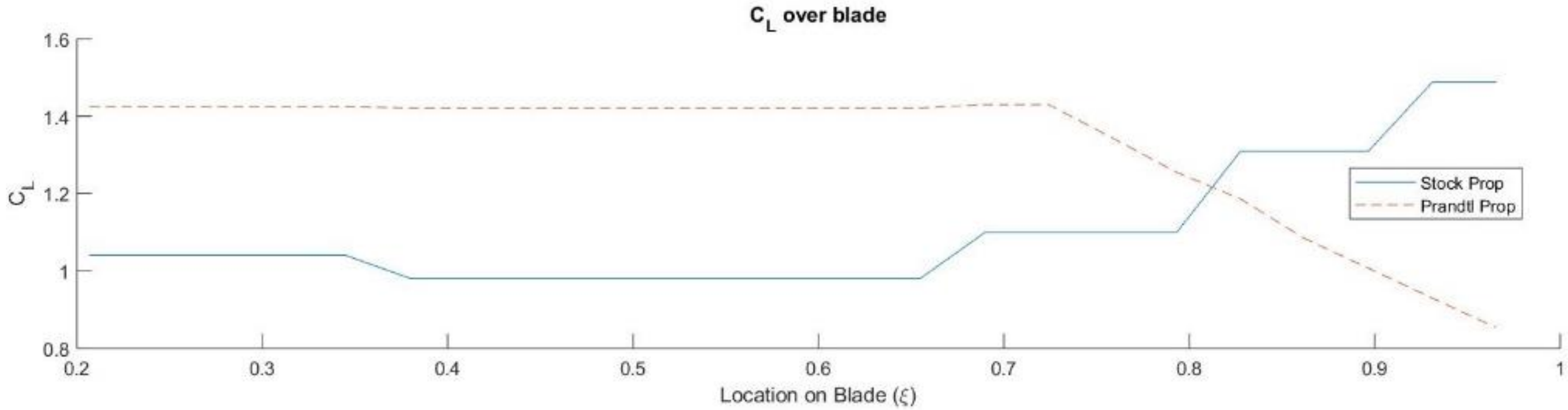
Methods – Resulting Designs



Methods – Resulting Loading







Methods – Need for New Design

- At design point, Stock prop and PIP do not have matching characteristics
  - Both Thrust and Torque increased
  - Efficiency lowered
- Change means that comparisons across multiple RPM and Velocities need to be made
- Created desire for new design that compares at design point
  - Reducing chord length decreases load
  - Resulted in equivalent thrust value at design point

```
Forces acting on stock Mejzlik Propeller
========================================
Prop Blade Loading: 0.32235    N
Prop Disk Loading: 0.011638    N
Thrust: 449.5598    N
Torque:   25.1571    Nm
Power:    15.8067    kW
Efficiency 1: 93.8558 %
Coefficient of Thrust: 0.13364
Coefficient of Power:   0.06491

Forces acting on Prandlt Inspired Propeller
===========================================
Prop Blade Loading: 0.37376    N
Prop Disk Loading: 0.013494    N
Thrust: 514.0189     N
Torque:   29.1696    Nm
Power:    18.3278    kW
Efficiency 1: 92.5514 %
Coefficient of Thrust: 0.1528
Coefficient of Power:   0.075263
```

Screenshot of Design Point Loading for Stock Prop and PIP

Methods – Work Flow

Designing Prandtl Prop 1.6.3

- stockprop.txt
- pranprop.txt
- pranprop2.txt

→

XRotor

- StockCase[RPM]_[form].txt
- PranCase[RPM]_[form].txt
- Pran2Case[RPM]_[form].txt

→

XRotor_Graphs_[form].m

- Performance Graphs
- CSVs with performance data

Forms:

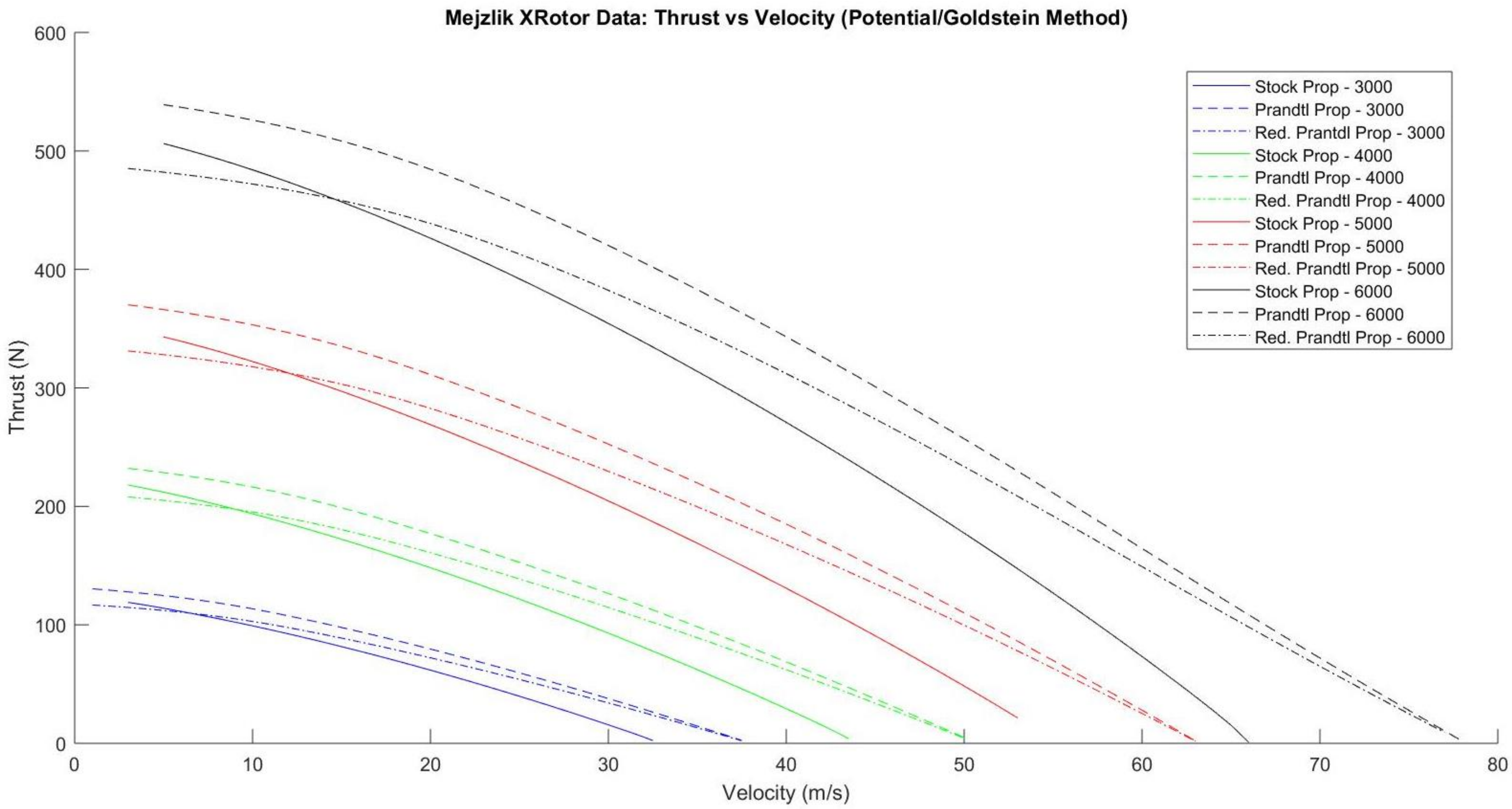
Potential - solves for the helically-symmetric potential flow about a rigid helicoidal wake

- High accuracy for standard propellers

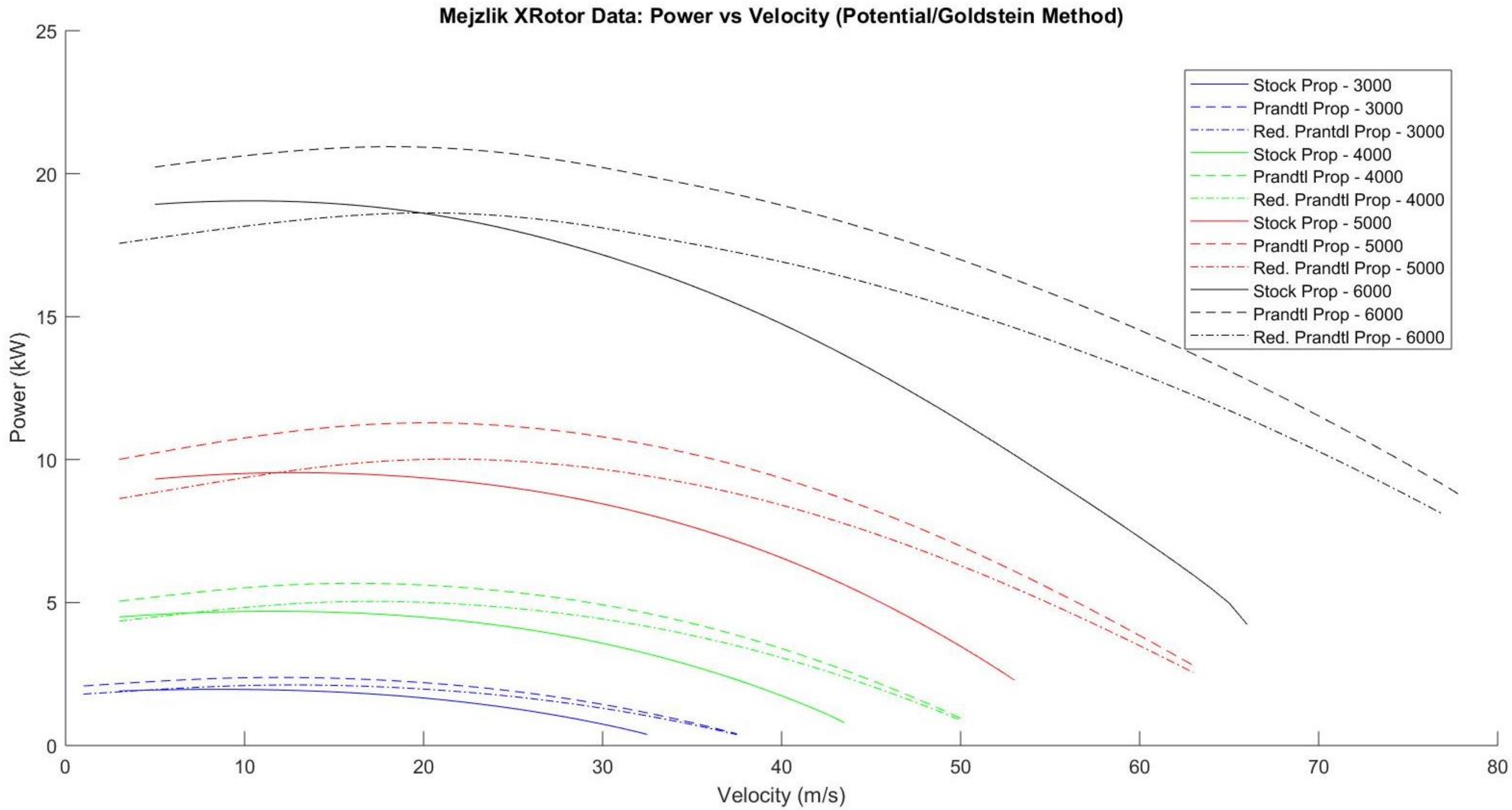
Vortex - uses a discrete vortex wake for induced velocity calculations

- More accurate for props with raked or swept lifting lines

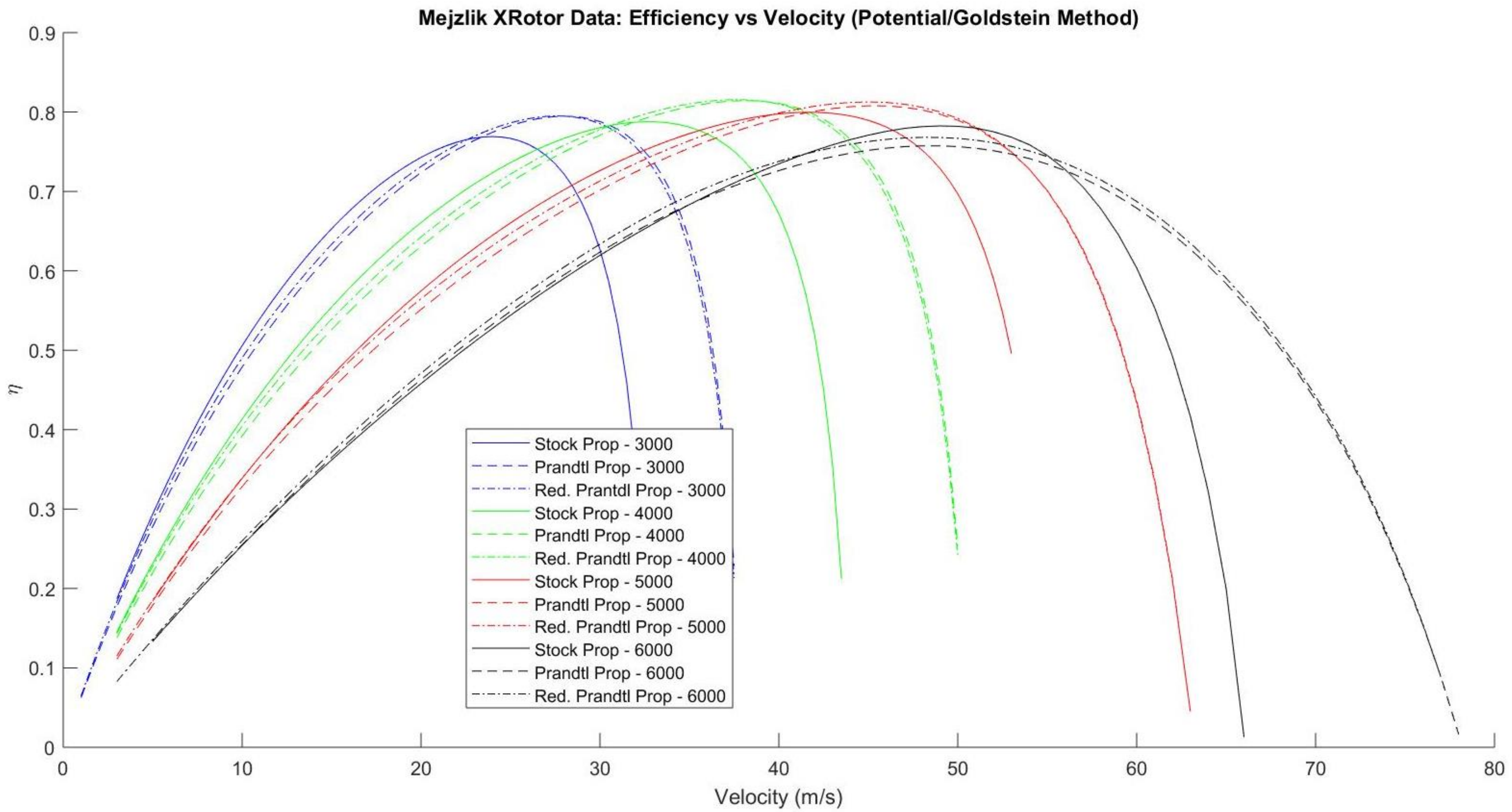
Graphs - Thrust



Graphs - Power



Graphs – Efficiency vs Velocity



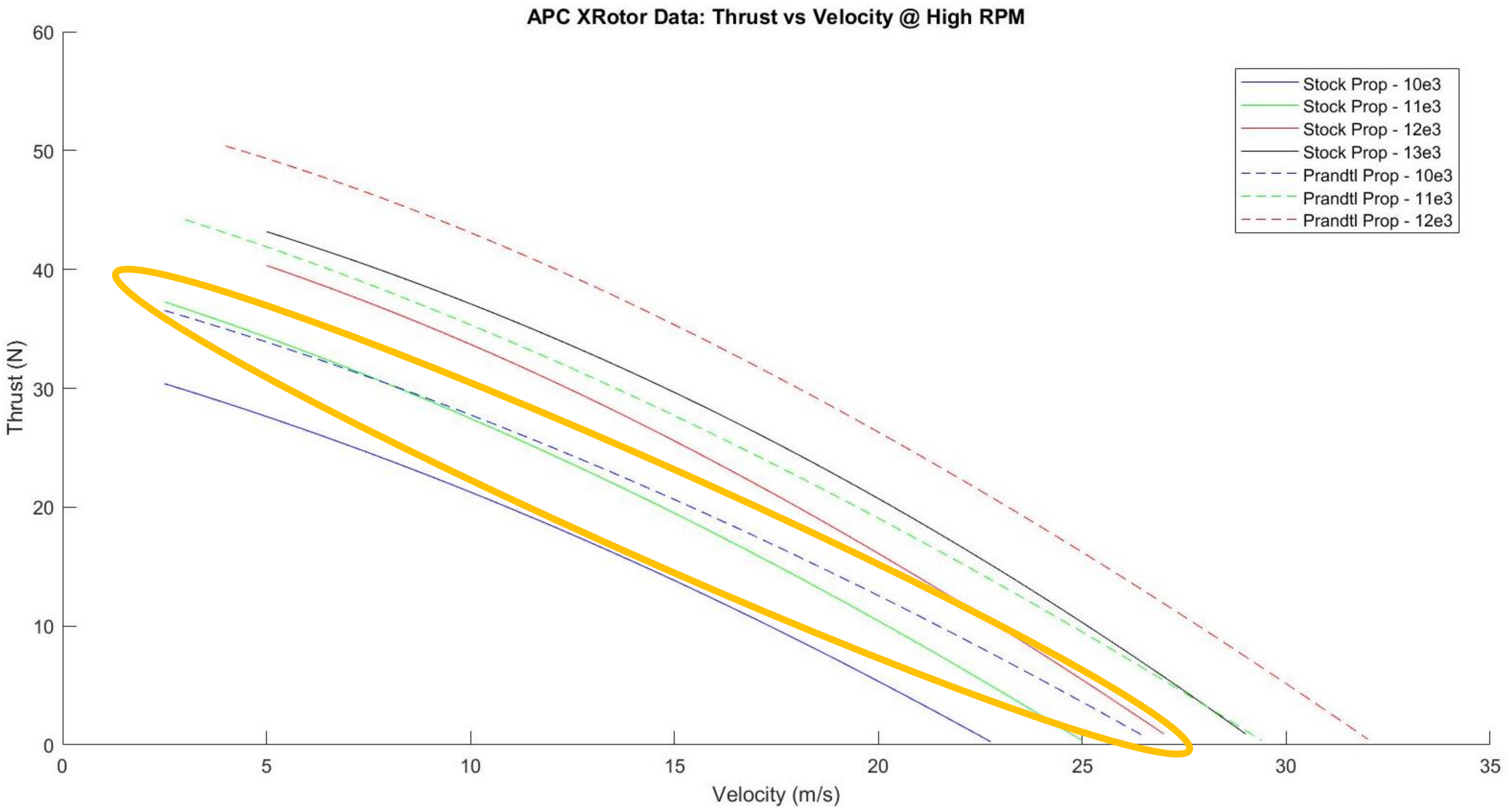
Results – PIP and PIP2

- PIP outperformed MIL prop at high advance ratios
  - Poor performances at low advance ratios
  - Low Static Thrust
    - Matches claims from qualitative testing
- No point where props produce same thrust, but PIP produces less torque at same velocity and RPM
  - Claim from previous testing/calculations was a 15% reduction in torque for equivalent thrust

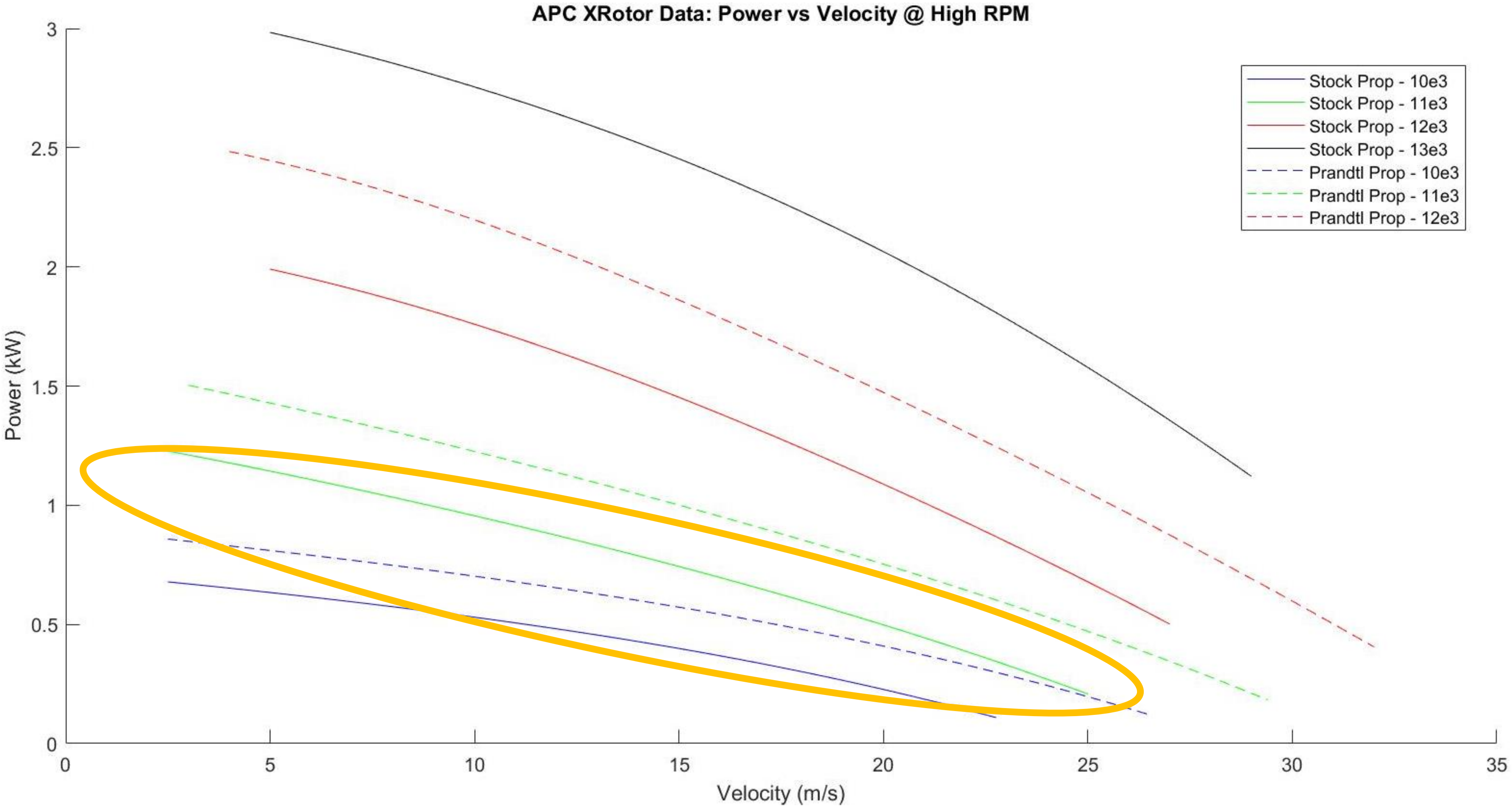
Tests of Previous Prandtl Prop Designs

- Old designs exist for a “Prandtl Propeller”
  - Various CSV files with data points for airfoils and beta angles
  - No clear design philosophy outlined
  - All values in the CSVs are just values, not formulas
    - No explanation of where values came from
- This design will be referred to from now on as the “Previous Prandtl Propeller” (PPP)

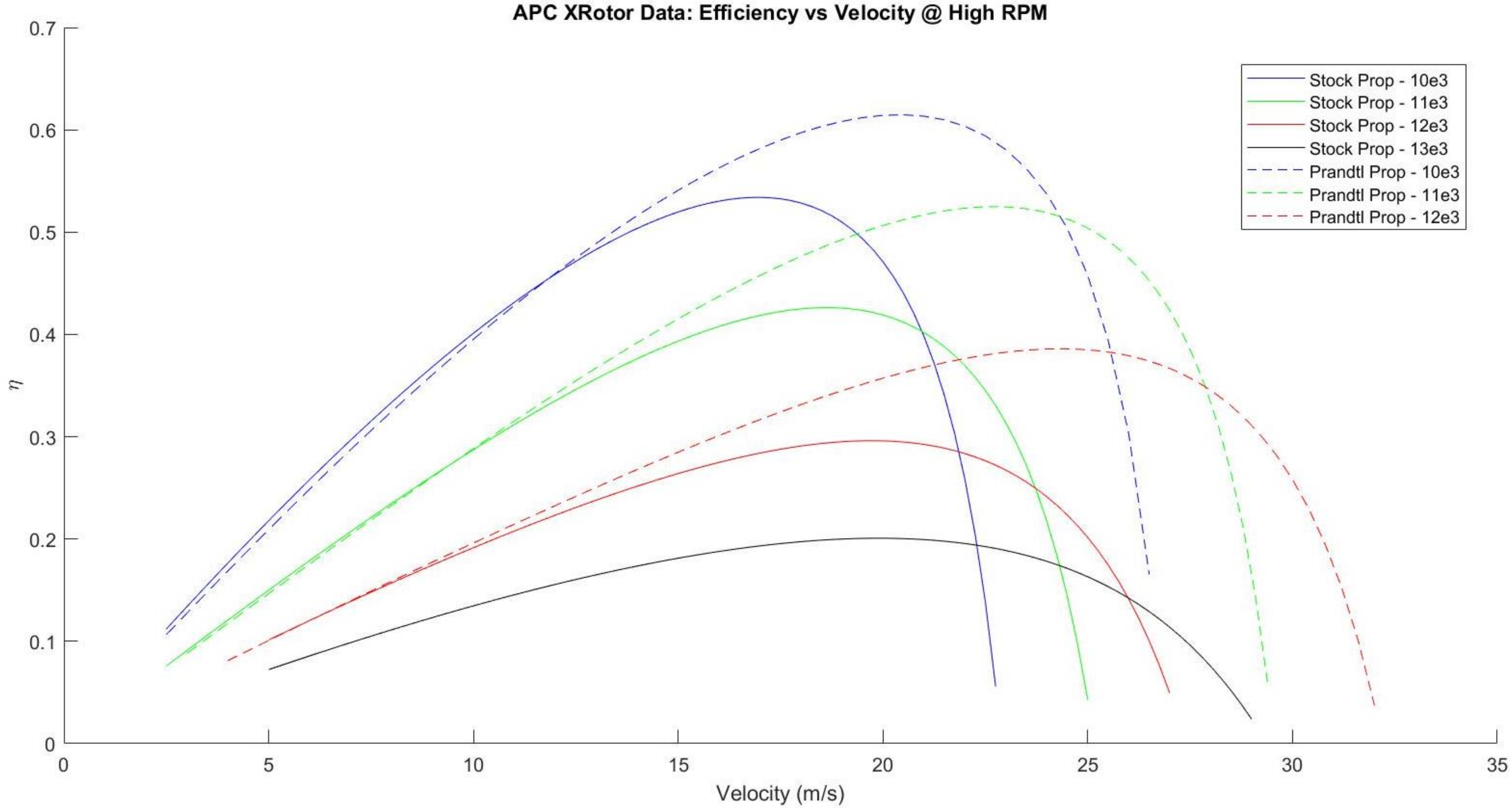
Graphs - Thrust



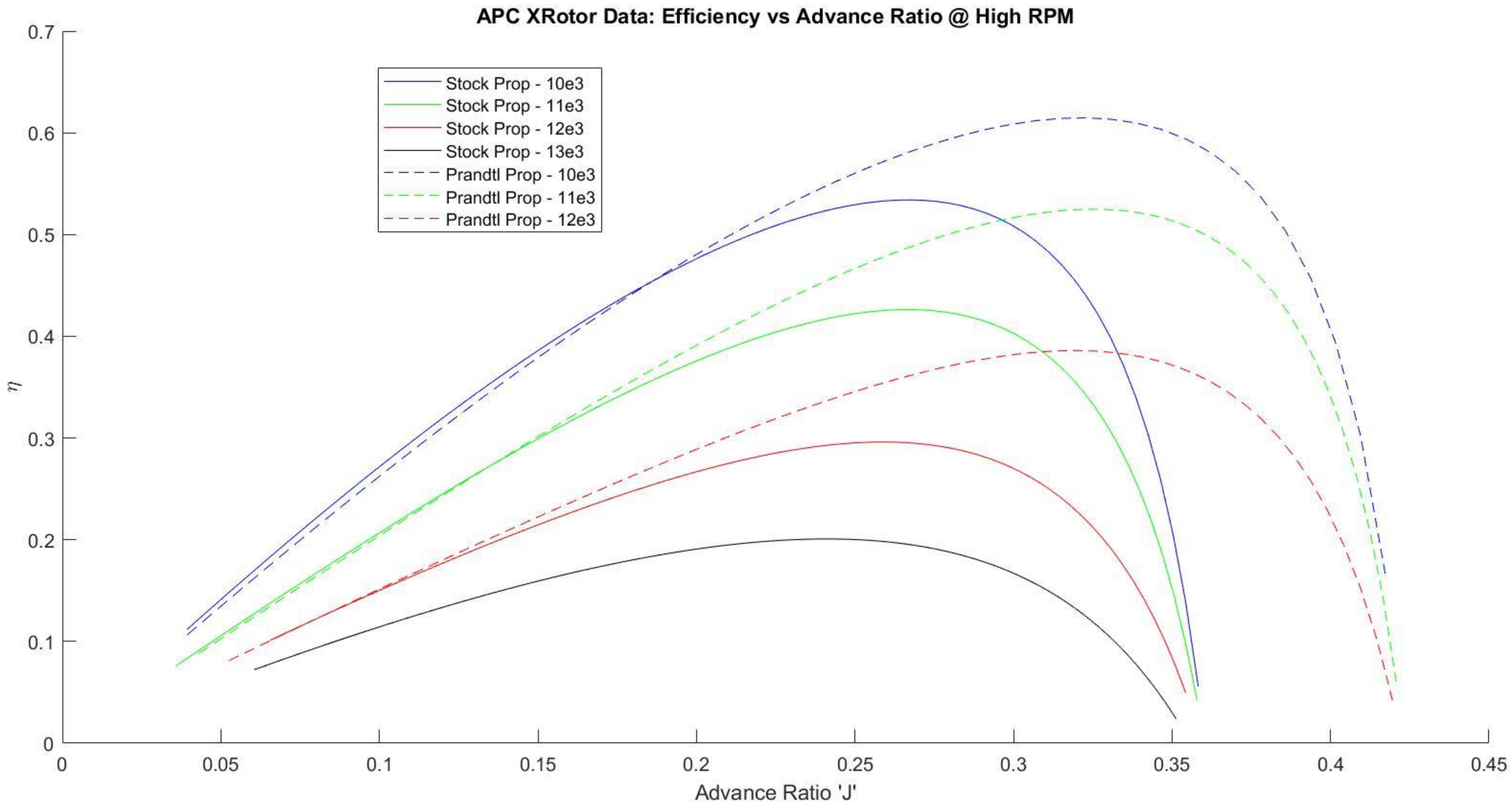
Graphs - Power



Graphs – Efficiency vs Velocity



Graphs – Efficiency vs Advance Ratio



Results – APC 15x6E and PPP

- PPP outperformed APC prop at high velocities
    - Efficiencies are slightly lower at low velocities, but not dramatically so
- Thrust graph clearly shows that the PPP appears to achieve a similar amount of thrust at lower RPM, and thus lower power
- No clear design point, so it's impossible to determine if the 15% reduction claim is accurate

Conclusions

- Previous results have not been verified
- Global Optimization has potential
- PIP has potential to improve torque and efficiency characteristics
- Difficult to say if PIP is better than or preferable to MIL props
  - Props are designed for a specific range
  - Results show conversion changes the range the PIP works over
- PPP shows dramatically increased efficiency at higher velocities compared to the APC 15x6E it was based on

Future Work for Project

- Improve DesigningPrandtlProp.m code
- Test physical models of PIP and Fan
- Extrapolate more data from existing Prandtl Prop designs
- Write algorithm to optimize over whole prop blade
- Derive a Prandtl Solution for propellers

Prandtl Fan Prototype 8

Lessons Learned

- Skills in XRotor and XFoil
- Aerodynamic principles
- Importance of validation through testing
- Importance of organization of data
- Communication skills
- Work diversity
- Perseverance through difficulties and searching for new angles

Internship Experience

- Work on PEGASUS Propellers
  - Testing of the N250 Propeller in XRotor
  - Evaluation of Propeller Geometries for the Aft, Inboard, and Wingtip propellers

Internship Experience

Future Plans

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University of the Pacific

Summer 2020

Fall 2020 & Spring 2021

Summer 2021

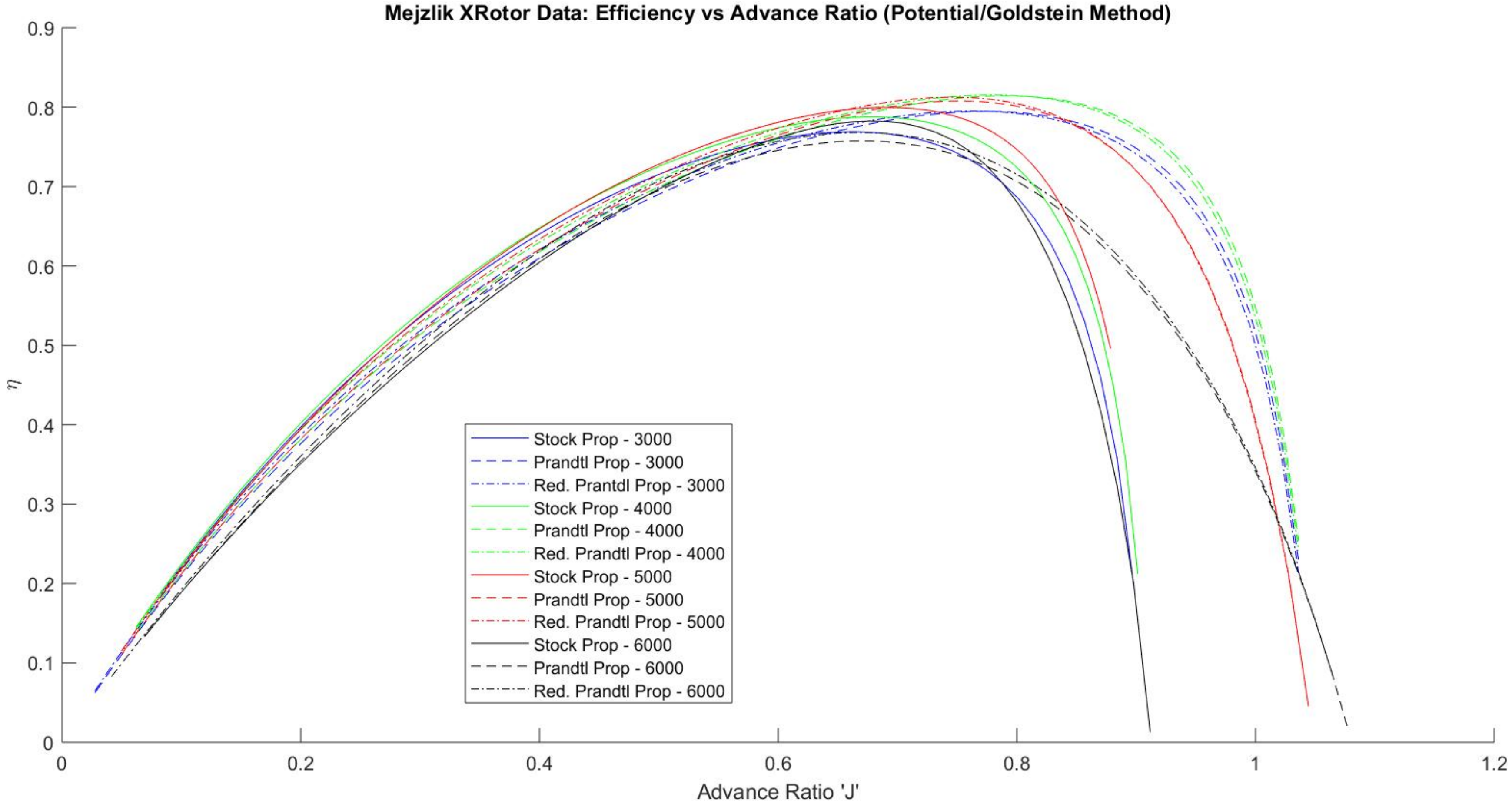
Acknowledgements

- Jason Lechniak
- Lisa Illowsky

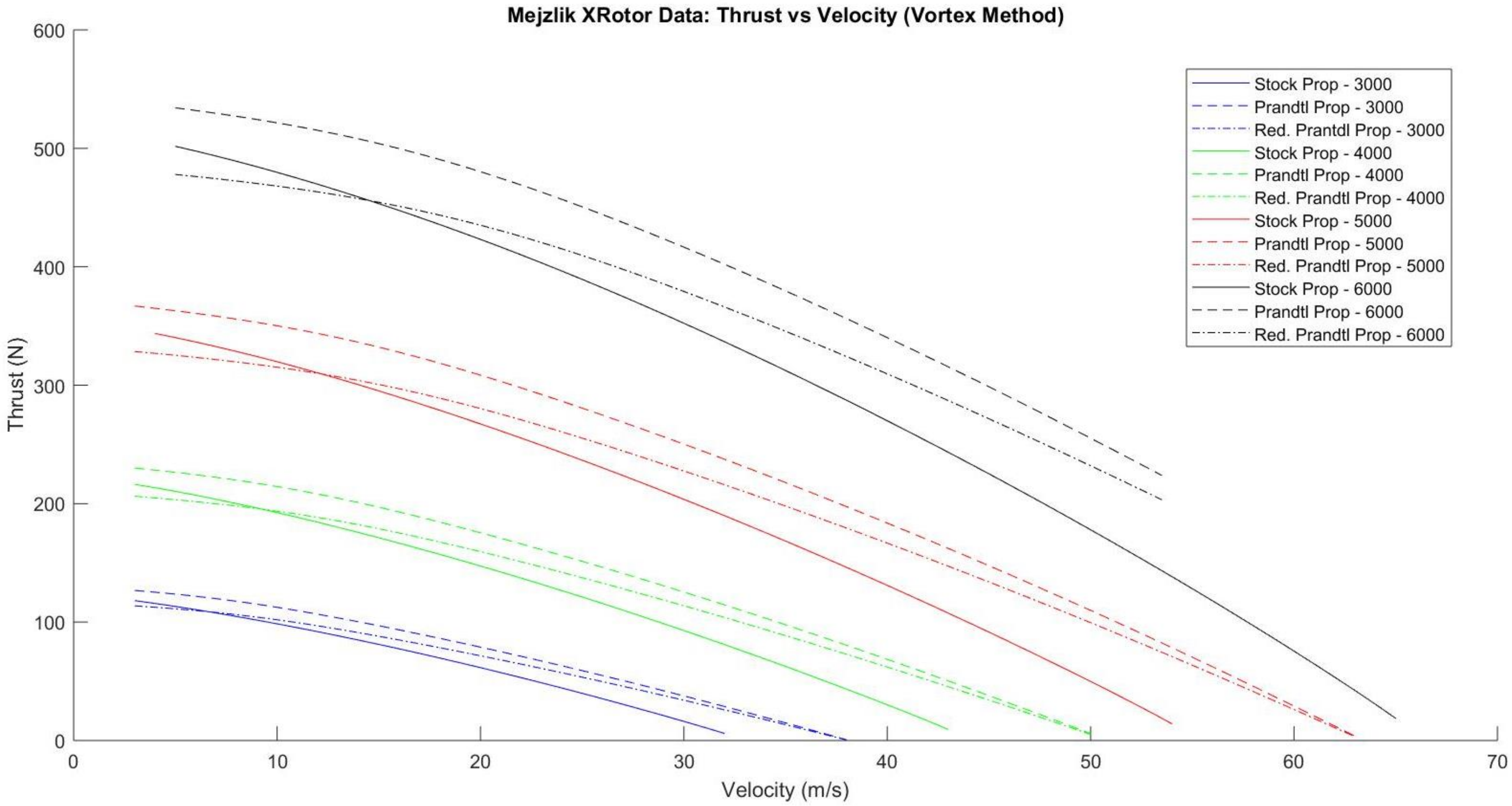
Questions?

Backup Slides

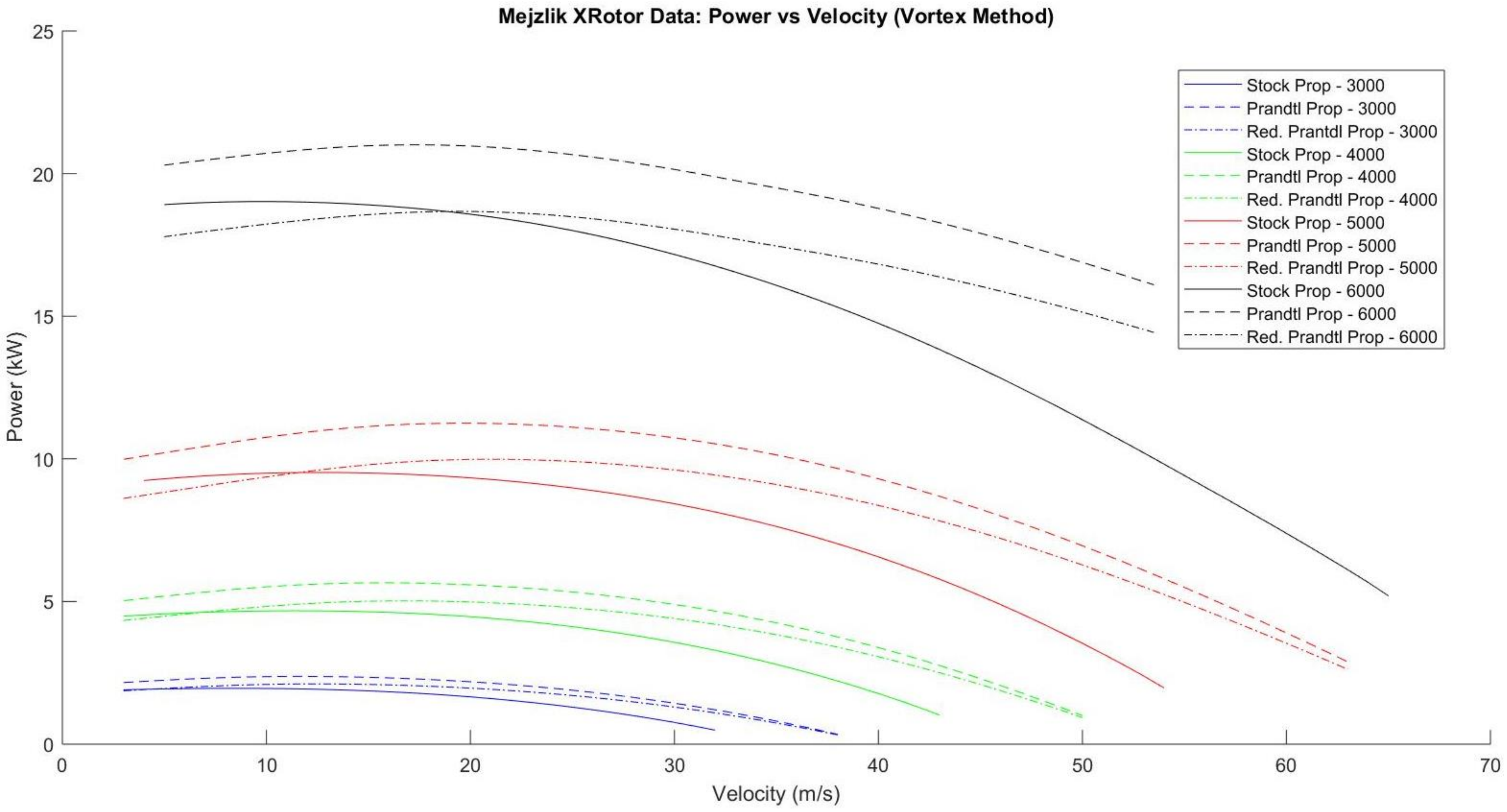
Graphs – Efficiency vs Advance Ratio



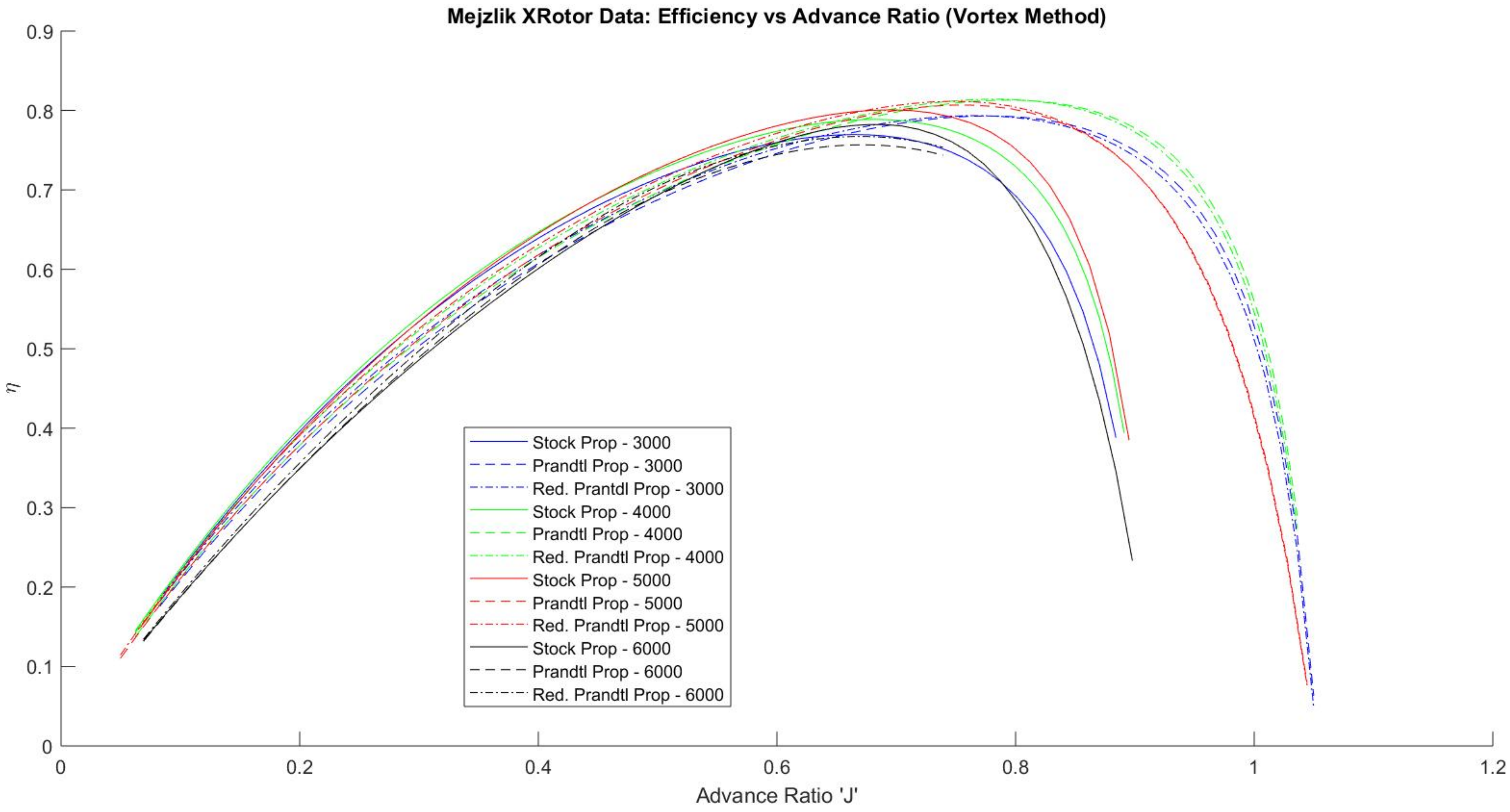
Graphs – Thrust (Vortex)



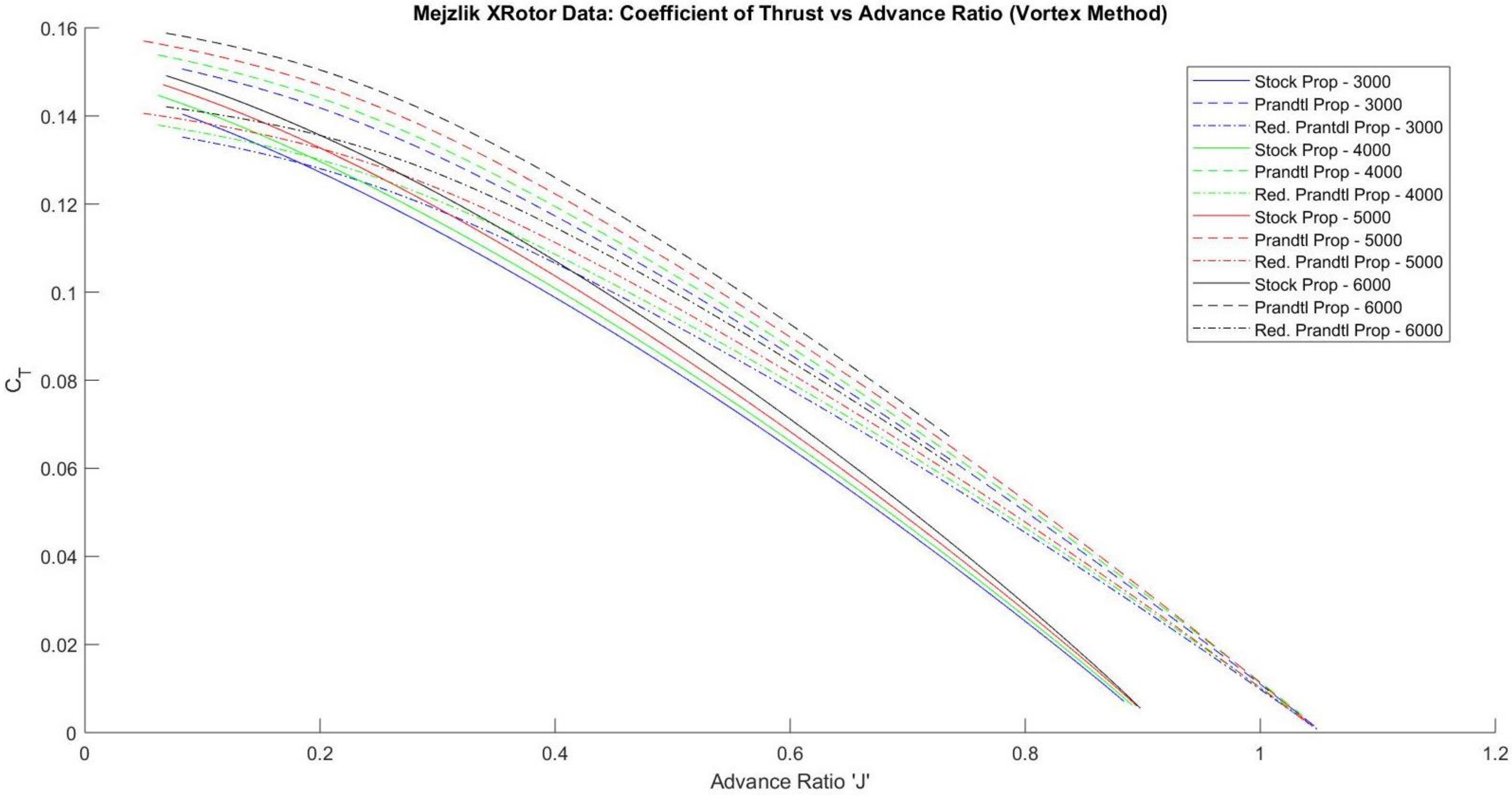
Graphs – Power (Vortex)



Graphs – Efficiency (Vortex)



Graphs – Coefficient of Thrust (Vortex)



Graphs – Coefficient of Power (Vortex)