National Aeronautics and Space Administration

Design of a Propeller with Global Minimum Torque

Matt Gray, *Electronics Engineer, NASA Langley Research Center*

Caleb Robb, *Aerospace Engineer, Oklahoma State University*

Todd Ferrante, *Mechanical Engineer, Analytical Mechanics Associates*

Al Bowers, *Chief Scientist (Retired), NASA Armstrong Flight Research Center*

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Problem/Need

- **Problem/Need**
  - **Advanced Air Mobility (AAM)**
    - Improved transportation method for public
  - **Urban Air Mobility (UAM) vehicles**
    - Technological viability
    - Public acceptance

- **Goal/Gap**
  - **Improve Noise Pollution**
  - **Improve Vehicle Efficiency**

Fig. 1: AAM Futuristic City-scape [1]


Fig. 2: LA-8 VTOL Vehicle [2]

Background/Motivation

- **Prandtl Wing "Bell" Span-load Theory**
  - **Developed by Al Bowers**
  - **Non-elliptical span-loading of wings**
  - **References:**
    - NASA/TP–2016219072
    - NASA/TM–20210014683
    - NASA Patent: 9,382,000
    - NASA Patent: 10,414,485

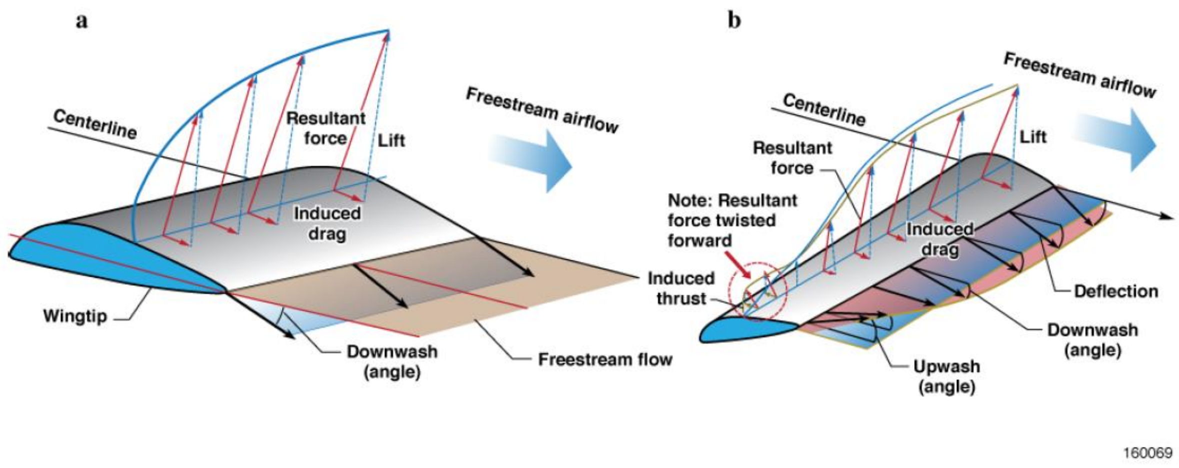

Fig. 3: Comparison of forces between traditional elliptical span-load (a) and Bell "Prandtl" span-load (b) [3]

Background/Motivation

- **Adapted to propeller design**
  - **Power In / Thrust Out**
    - Total Thrust Kept Constant → Minimize Total Torque
    - Calculus of Variations Optimization
  - **Global 3D solution of minimum torque**
    - Max lift coefficient inboard along blade-span then taper at ~72% span to ~20% lift
    - Reduced blade tip loading → reduces large shear layer intensity [4] → reduces noise
- **Trade Robustness for Efficiency**

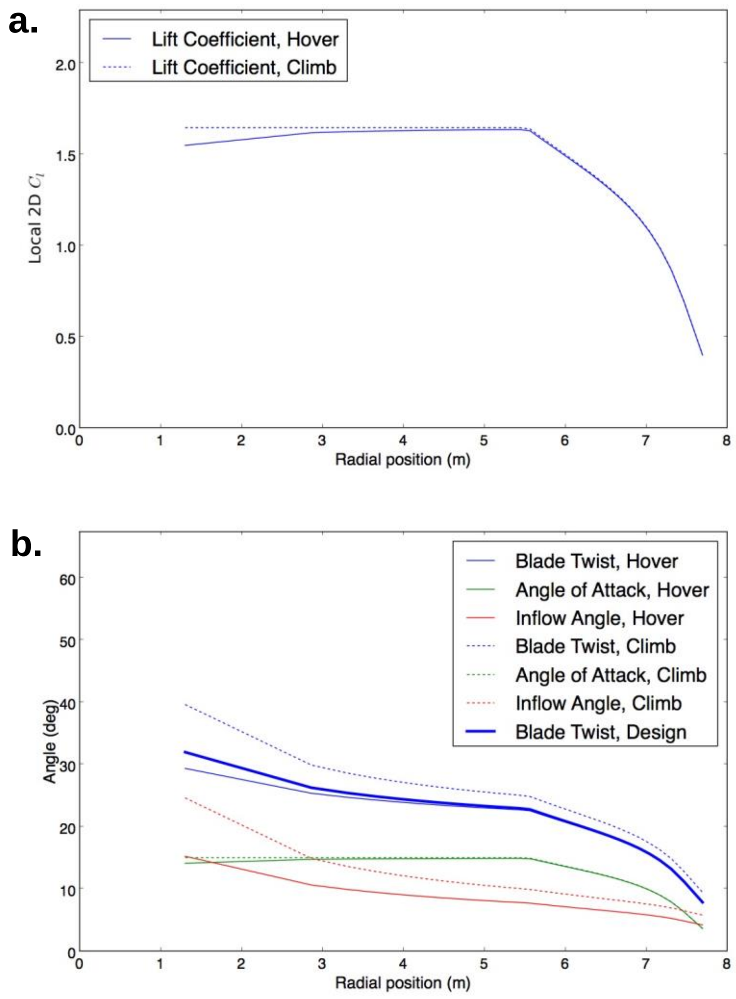

Fig. 4: Lift coefficient (a) and blade twist (b) characterization of 3D optimized propeller lift circulation

Design Methodology

- **Baseline Comparison Design:**
  - ***Minimum Induced Loss (MIL)***

- **Constants (MIL vs Novel “Prandtl”):**
  - **Diameter**
  - **“Pitch”**
  - **Advance Ratio Design Point**
  - **Chord Distribution**
  - **Camber Distribution of Airfoil**
  - **Material and Manufacturing**
  - **Drive System (Motors, ESCs, mounts, etc.)**
  - **Instrumentation**

- **Differences (MIL vs Novel “Prandtl”):**
  - **Twist Distribution (C_L / AOA)**

Design Methodology

- **Novel “Prandtl” Blade Design (Incremental Approach)**
  - **Phase I**
    - Bowers’ C_L Optimization → Blade Twist
    - Constant Chord
    - Constant Airfoil Distributions
  - **Phase II**
    - Bowers’ C_L Optimization → Blade Twist
    - Constant Chord
    - Non-Constant Airfoil Distributions
  - **Phase III**
    - Bowers’ C_L Optimization → Blade Twist
    - Non-Constant Chord
    - Non-Constant Airfoil Distributions

Phase I Design

- **Airfoil Choice**
  - **Optimized for Inboard Section**
    - Near Max C_L Operating Condition
  - **Two Standard Options**
    - NACA 6412
      - Slightly higher max C_L
    - MH 115
      - Good Stall Characteristics
      - Higher max C_L/C_D

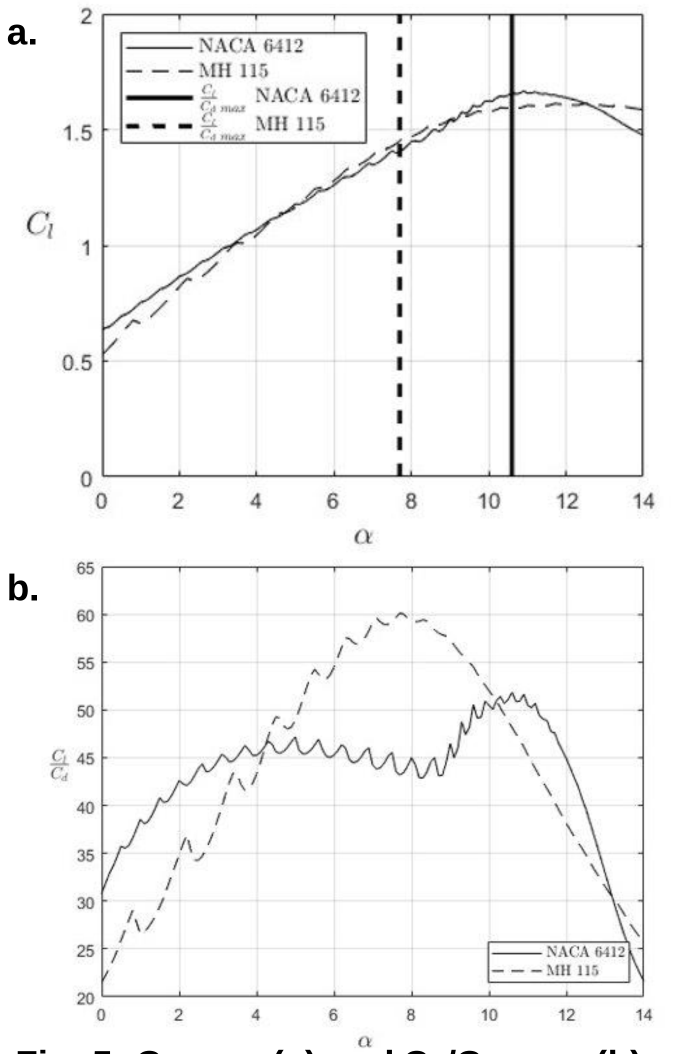

Fig. 5: C_L vs α (a) and C_L/C_D vs α (b) characterization of NACA 6412 vs MH 115 Airfoils

Phase I Design

➢ Parameters

- 2-Bladed
- *18-inch* Diameter
- Advance Ratio Design Point
  - *0.4*
- RPM Design Point
  - *3000*
- Freestream Velocity Design Point
  - *9.144 m/s*
- Blade Twist Based on Bowers' C_L Optimization
- Constant Chord
- Constant Airfoil

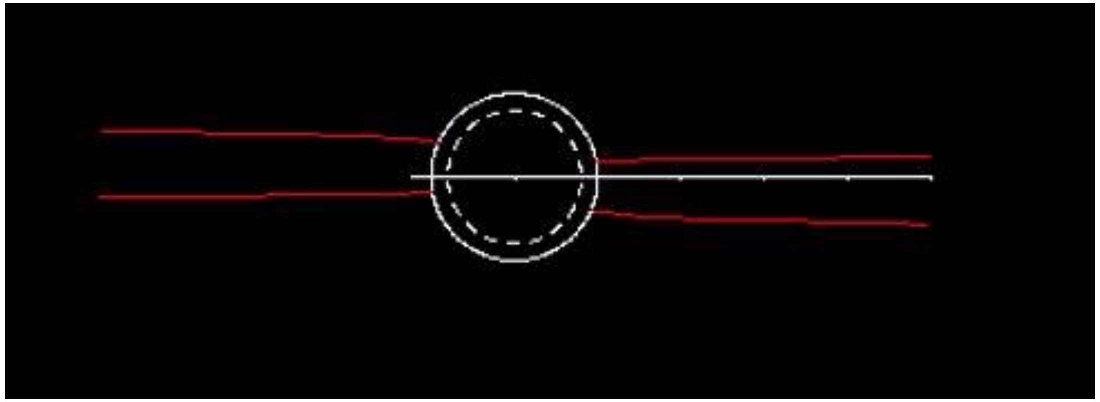

Fig. 6: XROTOR Representation of Phase I Propeller

Phase II Design

➢ Airfoil Choice

- **Decreasing Camber for Tip Airfoil**
- **Non-linear Transition from Root Airfoil to Tip Airfoil**
- **Less Twist Necessary at Tip**
  - Less Cambered Airfoil Reduced Tip Loading Instead of Angle of Attack (Twist)

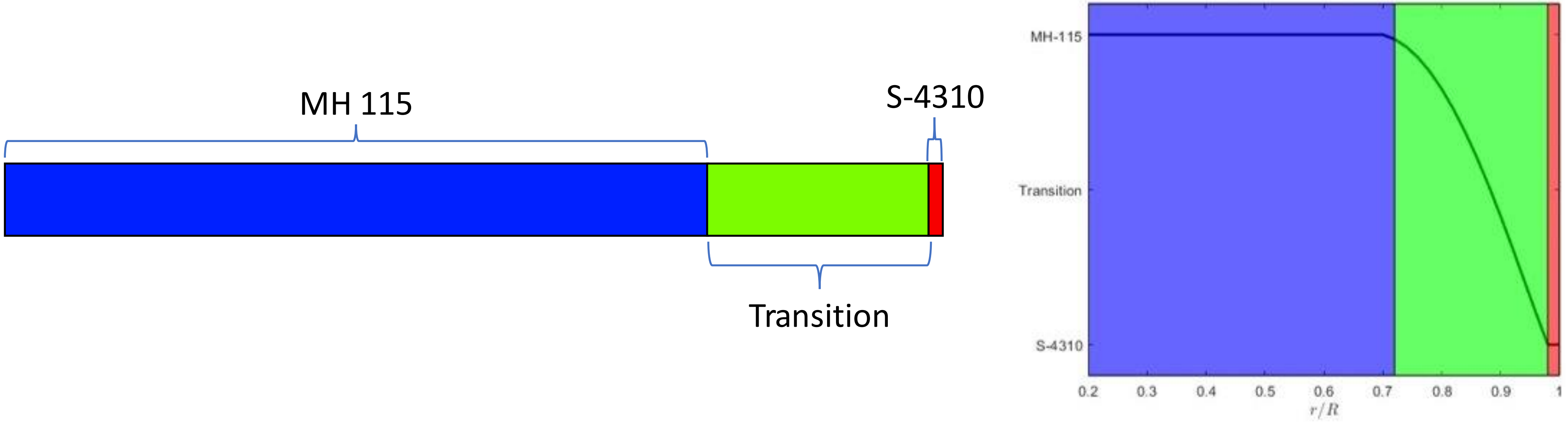

Fig. 7: Airfoil Distribution of Phase II Design: Inboard, Non-linear Transition, and Outboard Airfoils

Phase II Design

- **Parameters**
  - 18in (Same) Diameter
  - Nonlinear Airfoil Distribution
  - Exchanging Max C_L for Twist

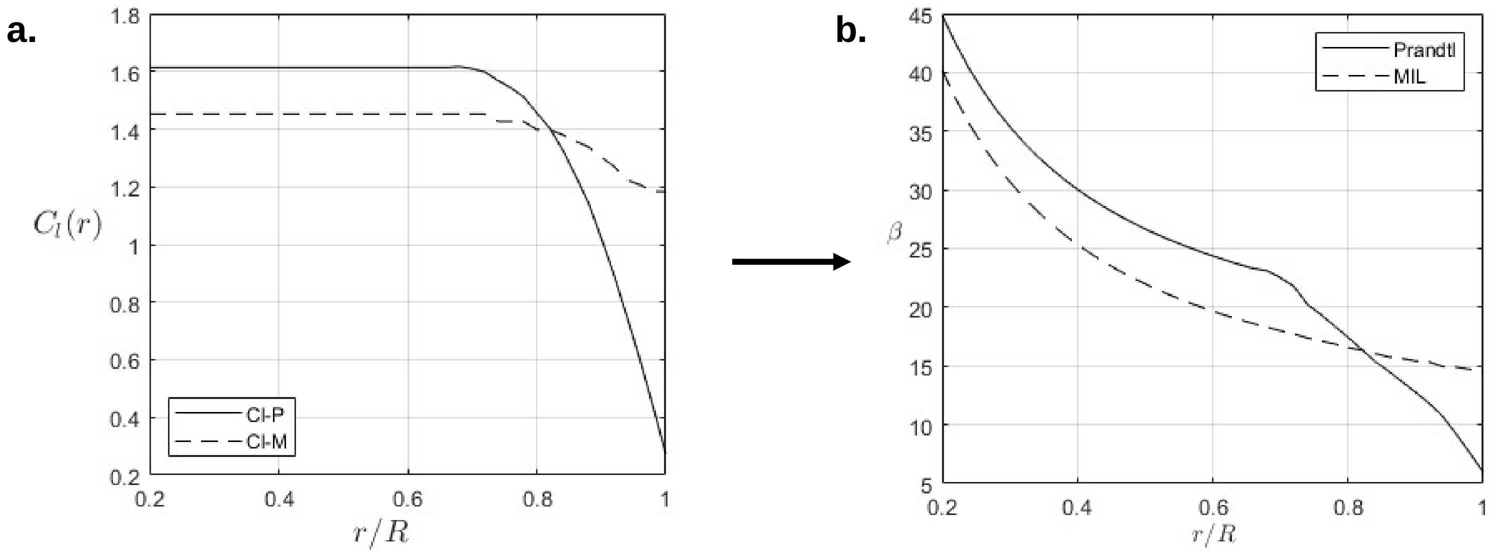

Fig. 8: C_L (a) and blade twist – β (b) of Phase II Design

Phase III (Final) Design

- **Parameters**
  - **18in (Same) Diameter**
  - **Same Airfoil Distribution**
  - **Chord Distribution Changes**

- **Conclusions**
  - **Efficiency Increase: *~2%***

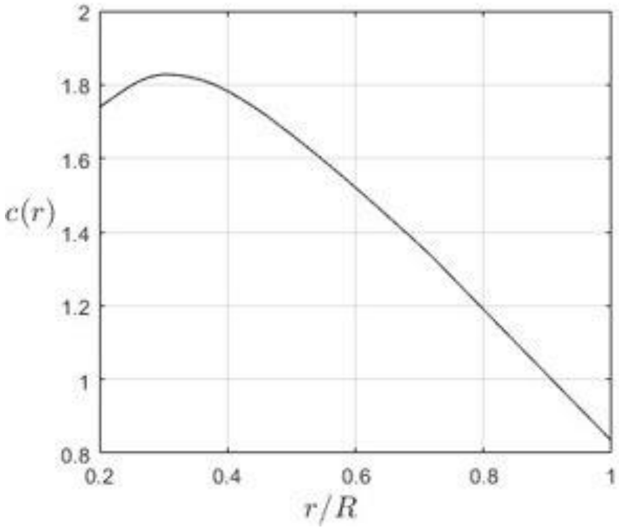

Fig. 9: Chord Distribution of Phase III Design

Table 1: 3000 RPM XROTOR Results for MIL (Baseline) and Prandtl (Novel) Propellers

	MIL	Prandtl
Thrust (N)	19.8	19.4
Torque (Nm)	1.02	0.98
C_T	0.14802	0.14468
C_P	0.10447	0.10056
Efficiency	0.5667	0.5754

Phase III (Final) Design Summary

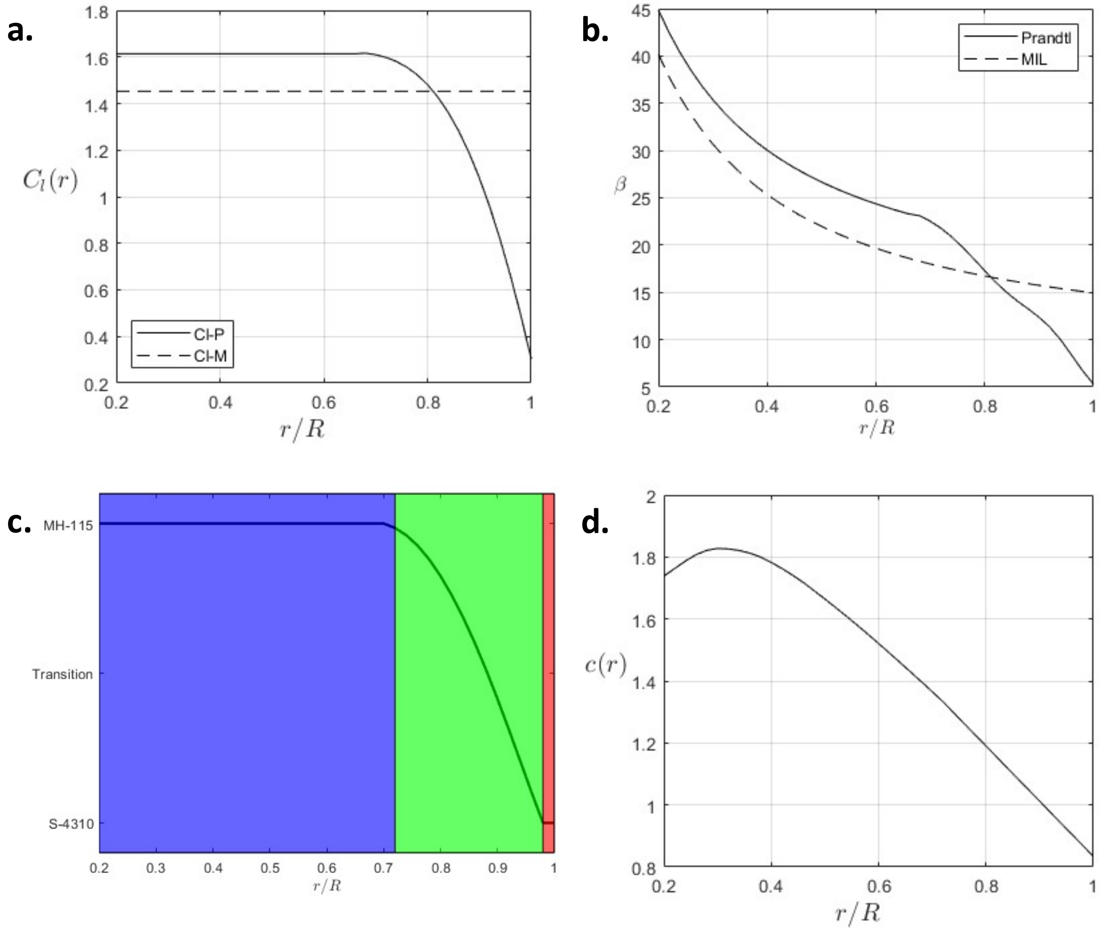

Fig. 10: Final (Phase III) Design of Prandtl and MIL propeller (a) Coefficient of Lift (C_l) distribution, (b) blade twist (β) distribution, (c) airfoil distribution, and (d) chord distribution

Combination Designs

- **Back off "100%" solution**
  - **Design in more robustness**
  - **Percentage between MIL and Prandtl blade twist along blade span**

- **7 Designs:**
  - **100% MIL (baseline)**
  - **100% Prandtl**
  - **Combo 1: 50% Prandtl / 50% MIL ("5050")**
  - **Combo 2: 60% Prandtl / 40% MIL ("6040")**
  - **Combo 3: 70% Prandtl / 30% MIL ("7030")**
  - **Combo 4: 80% Prandtl / 20% MIL ("8020")**
  - **Combo 5: 90% Prandtl / 10% MIL ("9010")**

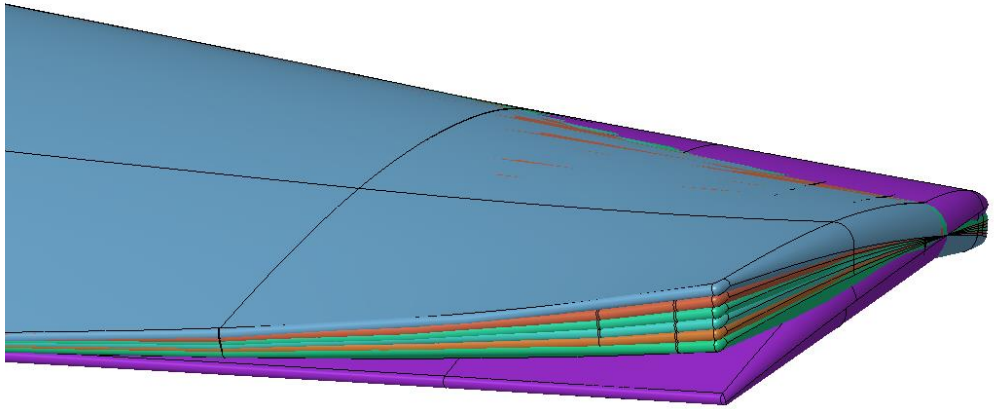

Fig. 11: Tip blade twists of MIL (purple) to Prandtl (blue) propeller blades with combo blades in-between.

Results (Final Design)

- **Advance Ratio Sweep – Prandtl, MIL, and Combo Blades**
  - **3000 RPM for All Runs**

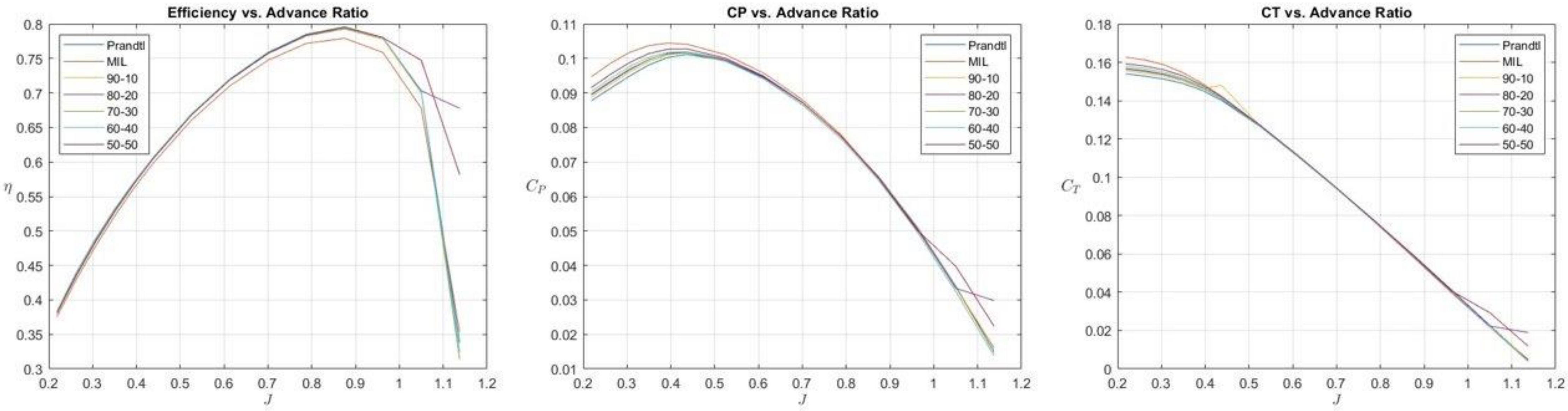

Fig. 12: Efficiency, C_P, and C_T vs Advance Ratio of MIL, Prandtl, and all Combo Propeller Designs

Results (Final Design)

- **Advance Ratio Sweep – Prandtl Only**
  - **2000, 3000, 4000, 6000, 8000 RPM**

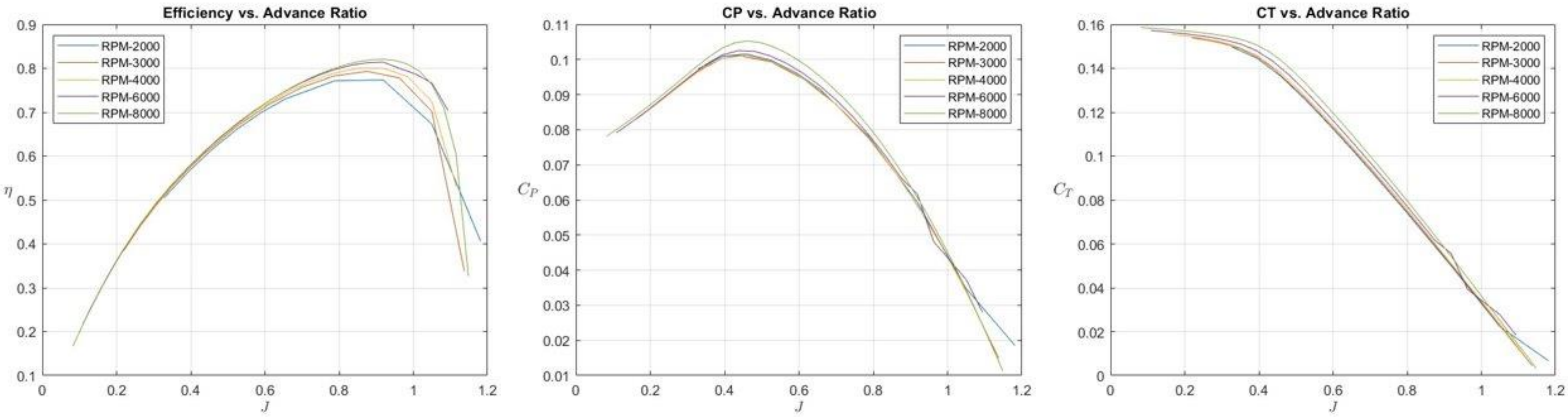

Fig. 13: Efficiency, C_P, and C_T vs Advance Ratio of Prandtl Design and Various RPMs

Future Work

- **Further Design Optimization**
  - **Airfoil Choice for Full-Scale → Not as Concerned with Reynold's Number Properties**
  - **Optimize Chord Distribution for Efficiency/Acoustics**
- **CFD Analysis of Propeller Blades to Determine Flow Field**
- **Acoustic Wind Tunnel Testing**
  - **Low Speed Acoustic Wind Tunnel (LSAWT) at NASA Langley**
- **Real-world Testing and Applicability of Propeller**
  - **Robustness vs Efficiency Tradeoff**

References

[1] NASA RVLT Project (*https://www.nasa.gov/directorates/armd/aavp/rvlt/*)

[2] North, David, D., Busan, Ronald, C., Howland, Greg, “Design and Fabrication of the Langley Aerodrome No. 8 Distributed Electric Propulsion VTOL Testbed”, NASA TM-20205011023, January 2021.

[3] Bowers, Albion, H., Murillo, Oscar, J., et al., “On Wings of the Minimum Induced Drag: Spanload Implications for Aircraft and Birds”, NASA TP-2016219072, March 2016.

[4] Marte, Jack E., and Donald W. Kurtz, *A Review of Aerodynamic Noise From Propellers, Rotors, and Lift Fans,* NASA-CR-107568, January 1970.