Efficient Variable-Pitch Propeller Aerodynamic Model Development for Vectored-Thrust eVTOL Aircraft

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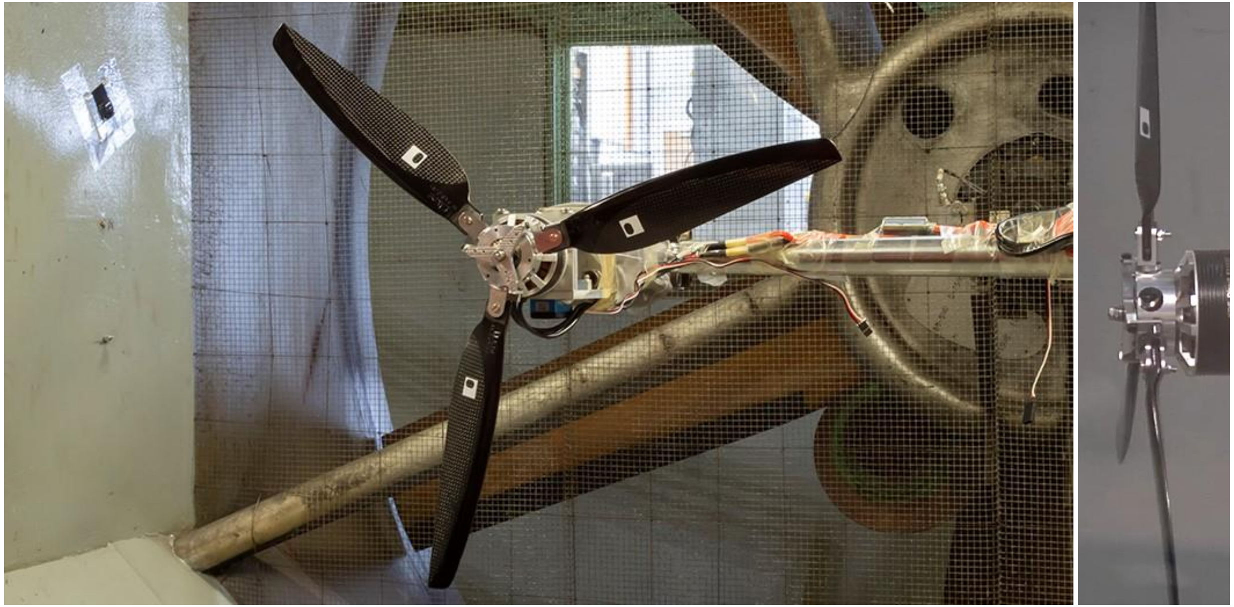
Contents

- Motivation
- Background
- Testing approach
- Sample results
- Concluding remarks

Software:
- Design-Expert®
- SIDPAC



Variable-pitch, 19.5-inch diameter propeller mounted in the NASA Langley 12-Foot Low Speed Tunnel.

Motivation/Background

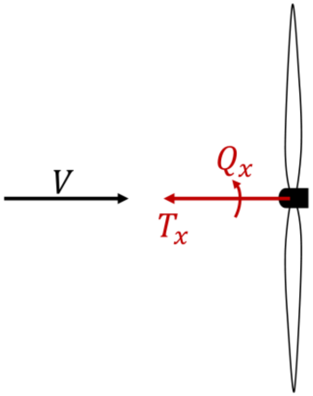
- **Objective:** develop a propeller aerodynamic model for a future eVTOL research aircraft for use in flight dynamics simulations
- eVTOL aircraft propellers experience a wide range of operating conditions
- Limited data or mathematical models exist for propellers at incidence
- Builds on previous work for fixed-pitch, eVTOL aircraft propellers[1,2,3]
- Variable-pitch control is important for certain eVTOL aircraft configurations

1. Simmons, B. M., "System Identification for Propellers at High Incidence Angles," *Journal of Aircraft*, Vol. 58, No. 6, 2021, pp. 1336–1350.
2. Simmons, B. M., and Hatke, D. B., "Investigation of High Incidence Angle Propeller Aerodynamics for Subscale eVTOL Aircraft," NASA TM-20210014010, May 2021.
3. Stratton, M., and Landman, D., "Wind Tunnel Test and Empirical Modeling of Tilt-Rotor Performance for eVTOL Applications," *AIAA SciTech 2021 Forum*, AIAA Paper 2021-0834, Jan. 2021.

Propeller Aerodynamics

Axial Propeller Aerodynamics

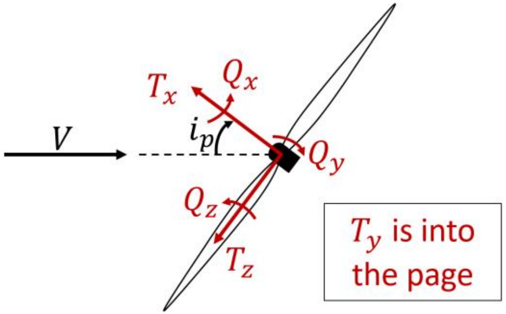
- Produces a thrust force T_x and aerodynamic torque Q_x
- Strong dependence on:
  - Advance ratio $J = V/nD$
  - Collective pitch angle δ_c
  - Propeller geometry
- May also be a function of:
  - Propeller blade Reynolds number Re
  - Tip Mach number M_{tip}
- Thrust and torque coefficients are defined as: $C_{T_x} = T_x/\rho n^2 D^4$ and $C_{Q_x} = Q_x/\rho n^2 D^5$



Axial propeller forces and moments.

Propeller Aerodynamics at Incidence

- Produces forces and moments in all axes
- Additional strong dependence on incidence angle i_p
- Important for modeling eVTOL vehicles

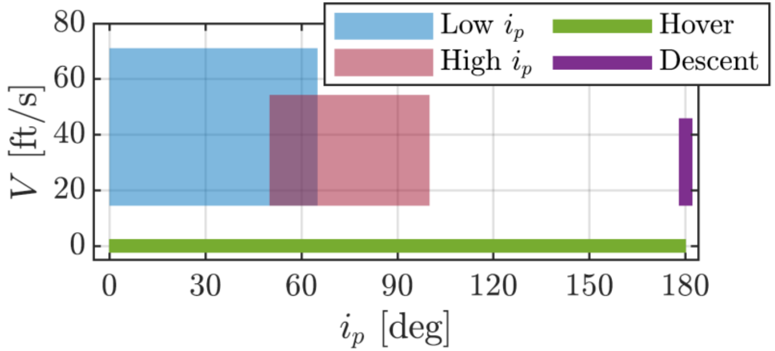


Propeller forces and moments at incidence.

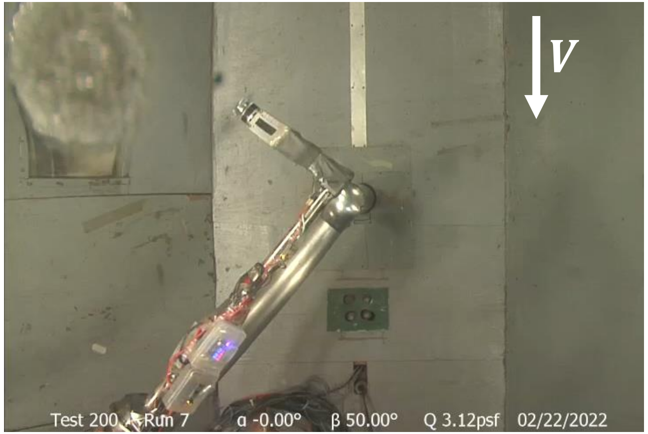
Propeller Wind Tunnel Test Overview

- NASA Langley 12-Foot Low-Speed Tunnel
- Test regions (informed by previous work[1,2])
  - Hover
  - Low Incidence (high-speed transition)
  - High Incidence (low-speed transition)
  - Descent
- Commanded test factors
  - Freestream velocity, V (**HTC**)
  - Incidence angle, i_p (**ETC**)
  - Motor PWM command, η_m (**ETC**)
  - Collective pitch PWM command, η_c (**ETC**)

ETC = easy-to-change factor
HTC = hard-to-change factor



Propeller test regions.



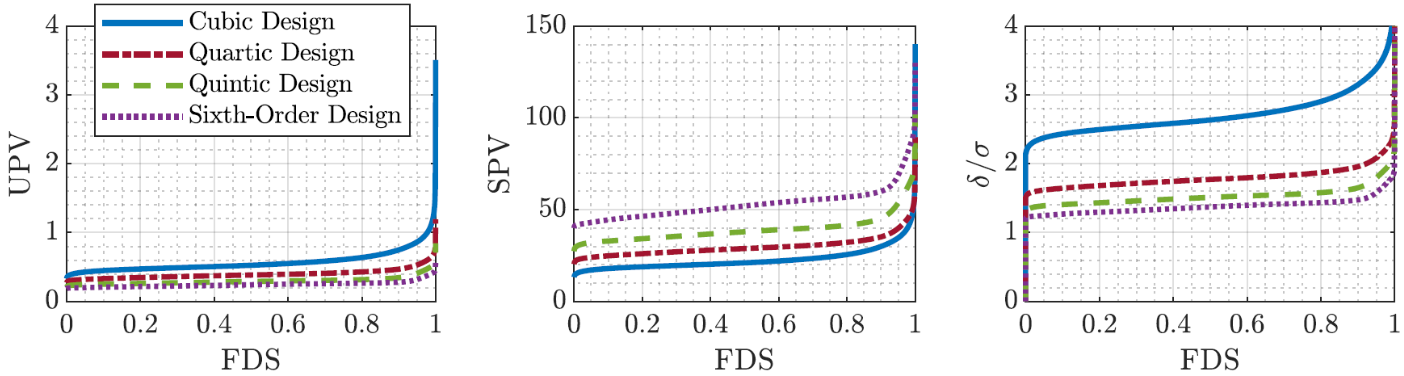
Wind tunnel run (x150 speed).

1. Simmons, B. M., "System Identification for Propellers at High Incidence Angles," *Journal of Aircraft*, Vol. 58, No. 6, 2021.
2. Simmons, B. M., and Hatke, D. B., "Investigation of High Incidence Angle Propeller Aerodynamics for Subscale eVTOL Aircraft," NASA TM-20210014010, May 2021.

Experimental Design Overview

- Design of experiments/response surface methodology (DOE/RSM)[1]
  - Hover Region: 2-factor completely randomized design
  - Low/High Incidence Region: 4-factor split-plot design
  - Descent Region: 3-factor split-plot design
- Different complexity I-optimal designs were compared
- Fraction of design space (FDS) plots[2,3] – see paper

Split-plot designs enable conducting efficient experiments with HTC factors.

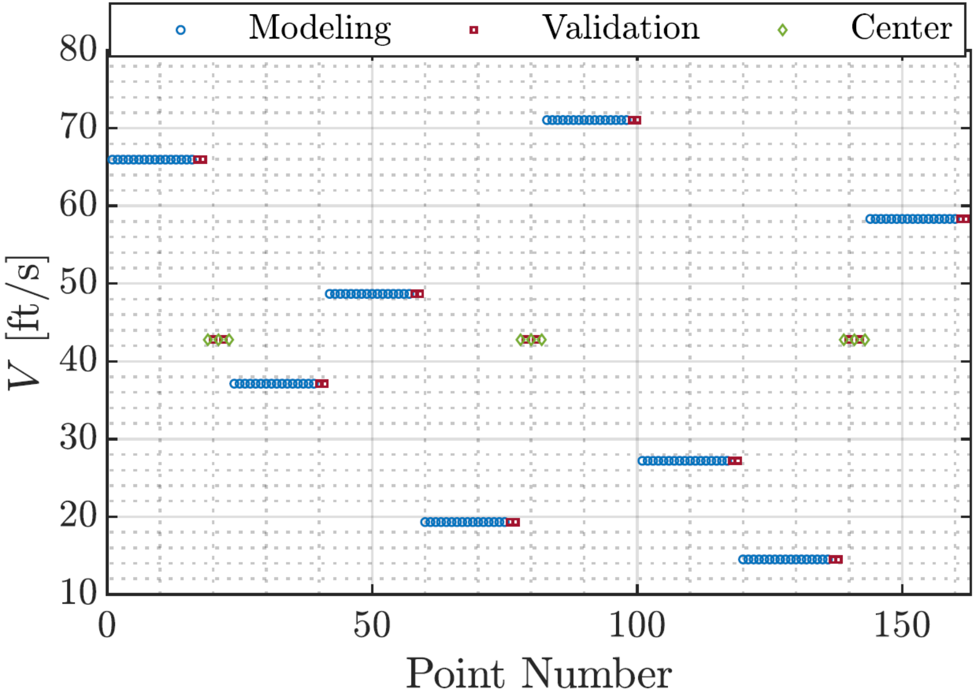


UPV – unscaled prediction variance
SPV – scaled prediction variance
δ – confidence interval half-width
σ – response standard deviation

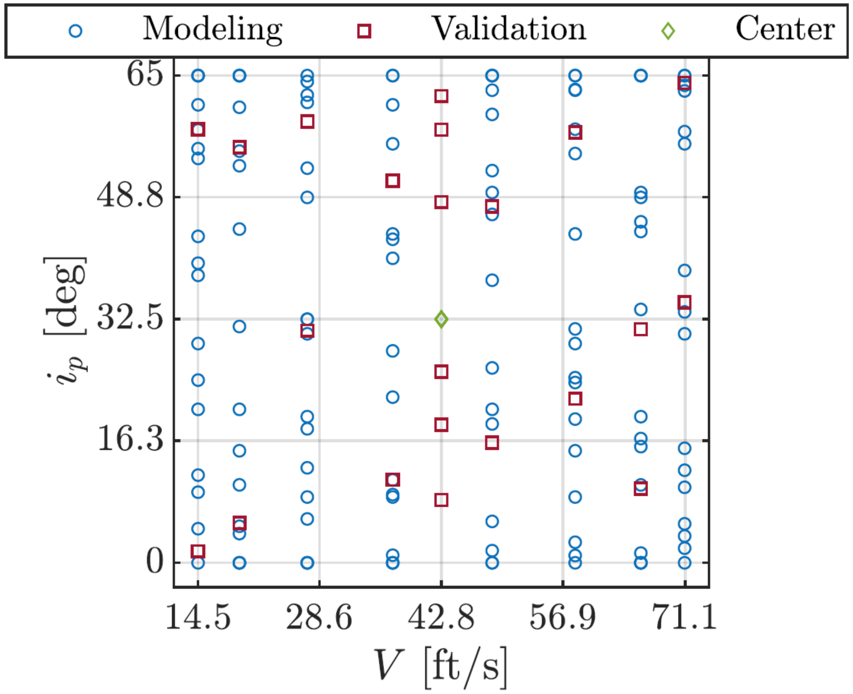
Low and High Incidence Region FDS plots for a cubic evaluation model.

1. Myers, R. H., Montgomery, D. C., and Anderson-Cook, C. M., *Response Surface Methodology: Process and Product Optimization Using Designed Experiments,* 4th ed., John Wiley & Sons, 2016.
2. Zahran, A., Anderson-Cook, C. M., and Myers, R. H., "Fraction of Design Space to Assess Prediction Capability of Response Surface Designs," *Journal of Quality Technology*, Vol. 35, No. 4, 2003.
3. Liang, L., Anderson-Cook, C. M., and Robinson, T. J., "Fraction of Design Space Plots for Split-plot Designs," *Quality and Reliability Engineering International*, Vol. 22, No. 3, 2006.

Low Incidence Region Test Matrix (1/2)

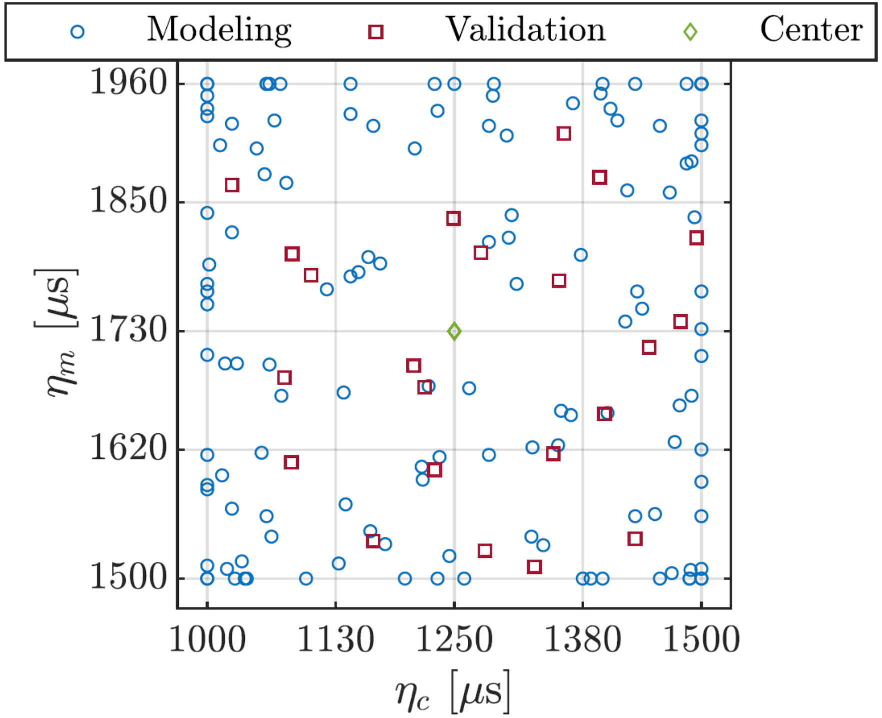


Freestream velocity against test point number.

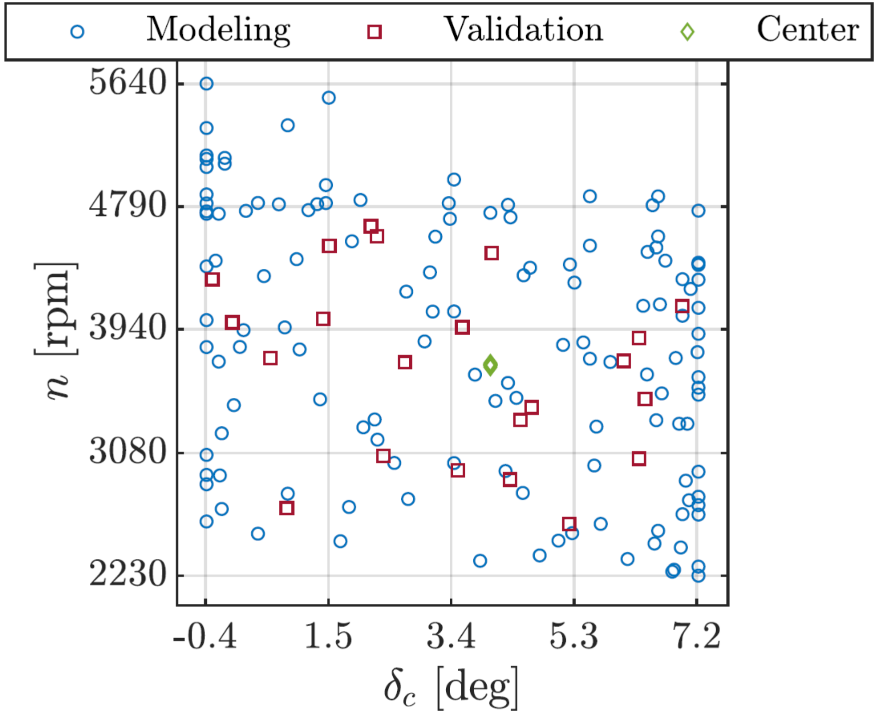


Incidence angle against freestream velocity.

Low Incidence Region Test Matrix (2/2)

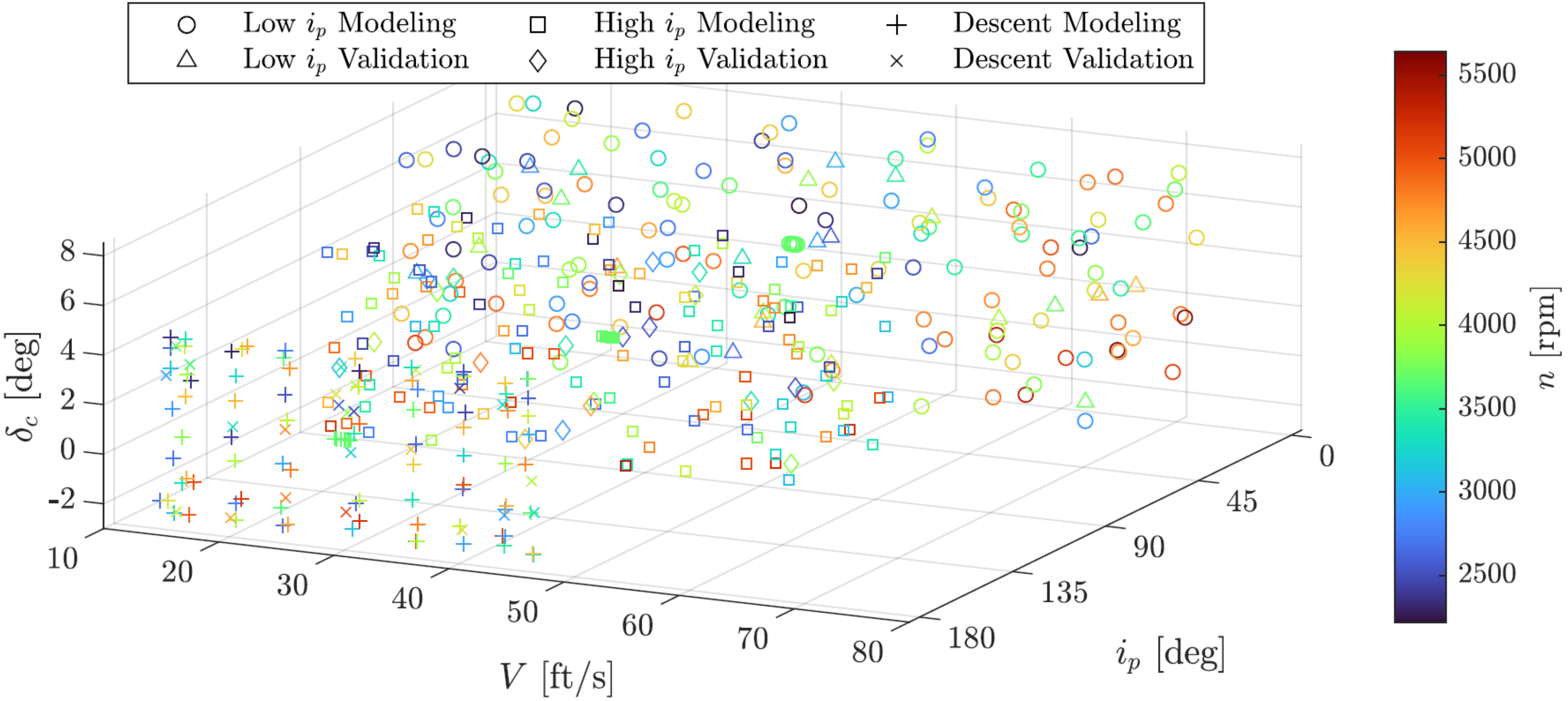


Motor command against collective command.



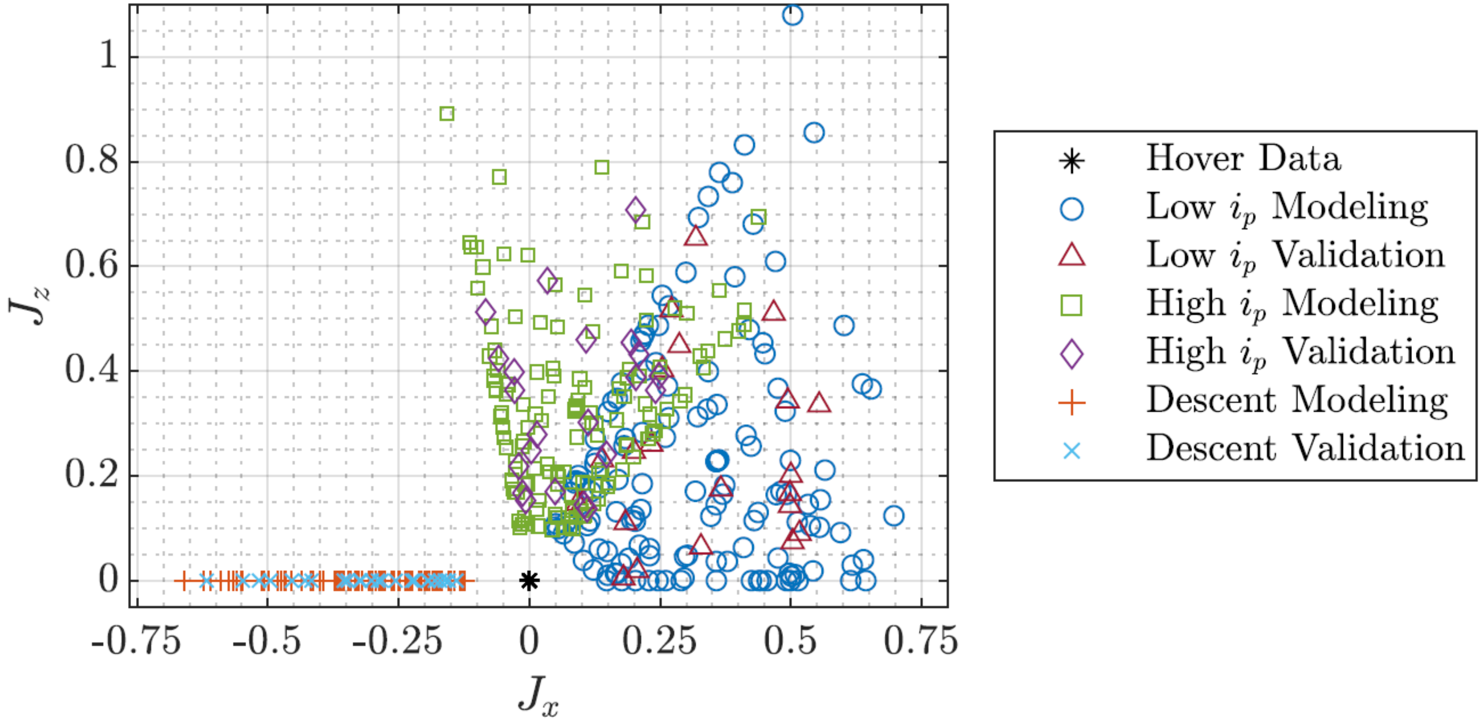
Observed rotational speed against collective pitch angle.

Test Overview for Multiple Regions (1/2)



Observed propeller test variable values for multiple test regions.

Test Overview for Multiple Regions (2/2)



$$J_x = \frac{V \cos i_p}{n\,D}$$

$$J_z = \frac{V \sin i_p}{n\,D}$$

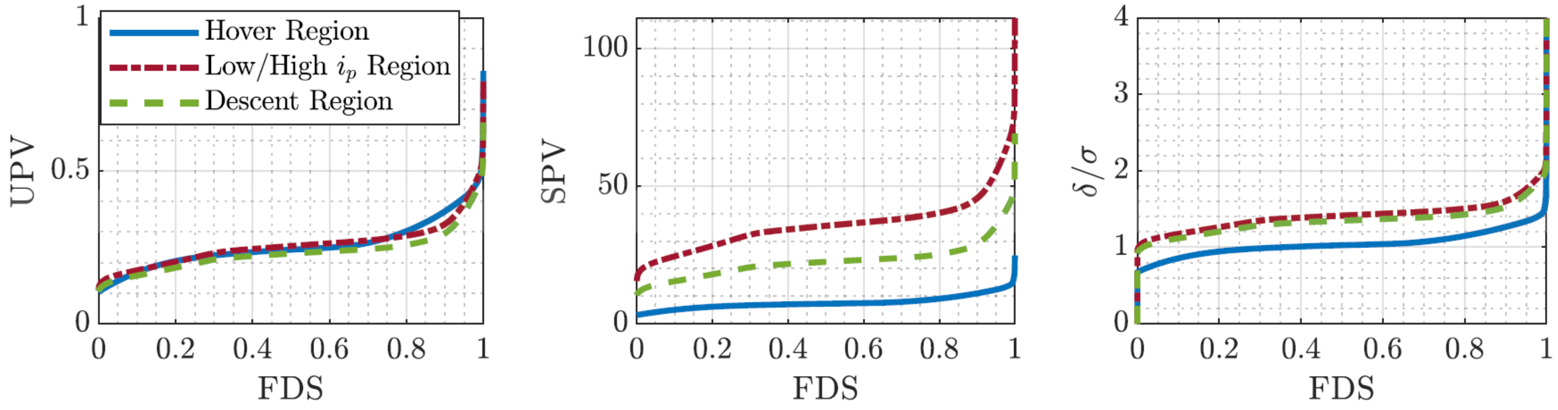
Observed advance ratio components in each experimental region.

Final Experimental Design Properties

Final experimental design properties for each test region.

Design Order	Points	Groups	Cubic Model FDS with $\delta/\sigma \leq 2$	Quartic Model FDS with $\delta/\sigma \leq 2$
Hover Region	36	N/A	1.000	0.999
Low/High Incidence Region	162	11	0.993	0.864
Descent Region	122	12	0.997	0.963

Data collection completed in less than 3.5 hours



Final design FDS plots for a cubic evaluation model in each test region.

Propeller Aerodynamic Modeling Approach

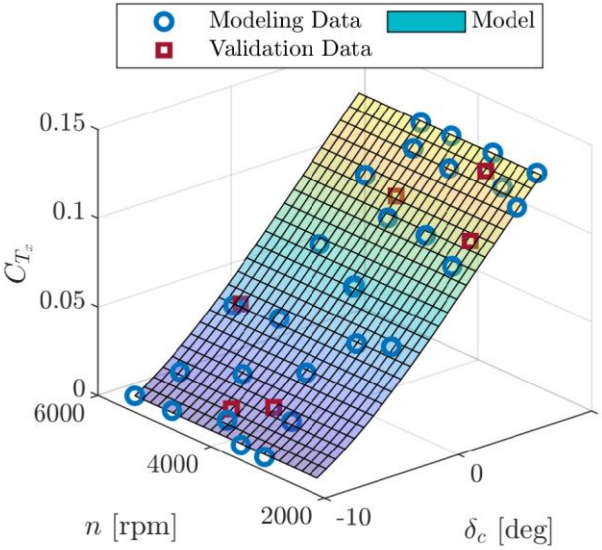
- Nonlinear polynomial models with up to cubic regressors
- Models identified using multivariate orthogonal function modeling[1,2]
- Response variables:
  - Propeller force coefficients: $C_{T_x} = \frac{T_x}{\rho n^2 D^4}$, $C_{T_y} = \frac{T_y}{\rho n^2 D^4}$, $C_{T_z} = \frac{T_z}{\rho n^2 D^4}$
  - Propeller moment coefficients: $C_{Q_x} = \frac{Q_x}{\rho n^2 D^5}$, $C_{Q_y} = \frac{Q_y}{\rho n^2 D^5}$, $C_{Q_z} = \frac{Q_z}{\rho n^2 D^5}$
- Final explanatory variables (others compared in the paper):
  - Normal advance ratio: $J_x = \frac{V \cos i_p}{n\, D}$
  - Edgewise advance ratio: $J_z = \frac{V \sin i_p}{n\, D}$
  - Collective pitch angle: δ_c
  - Rotational speed: n – describes both Re and M_{tip} effects
- Example model equation (thrust coefficient in the Low Incidence Region):

$$C_{T_x} = C_{T_{x_o}} + C_{T_{x_{J_x}}} J_x + C_{T_{x_{\delta_c}}} \delta_c + C_{T_{x_{J_x^2}}} J_x^2 + C_{T_{x_{J_z}}} J_z + C_{T_{x_{J_x \delta_c}}} J_x \delta_c$$

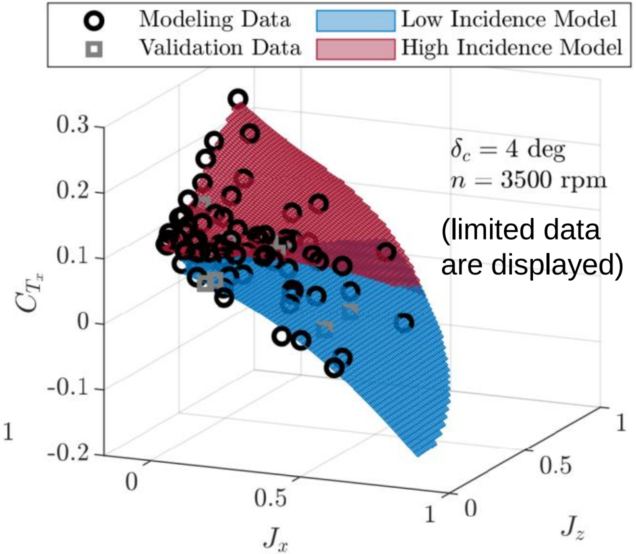
1. Morelli, E. A., and Klein, V., *Aircraft System Identification: Theory and Practice*, 2nd ed., Sunflyte Enterprises, Williamsburg, VA, 2016.
2. Morelli, E. A., "Global Nonlinear Aerodynamic Modeling Using Multivariate Orthogonal Functions," *Journal of Aircraft*, Vol. 32, No. 2, 1995, pp. 270–277.

Modeling Results

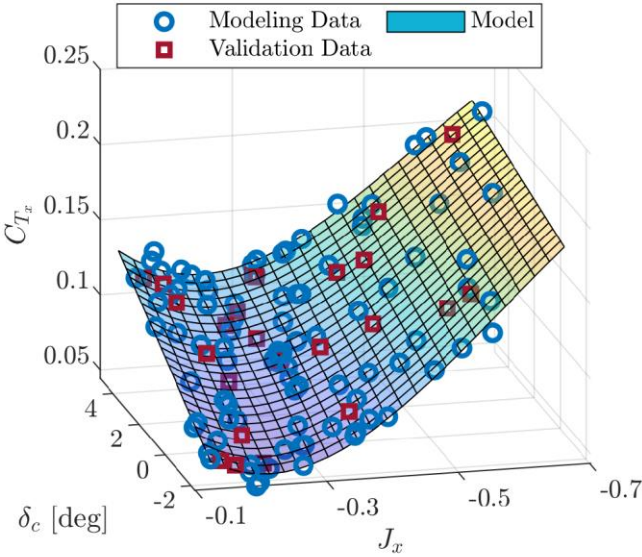
- The models have good predictive capability
- The final models are tabulated in the paper



Hover Region



Low and High Incidence Region



Descent Region

Thrust coefficient (C_{T_x}) response surface models compared to measured data.

Concluding Remarks

- The variable-pitch propeller testing/modeling strategy was successful and is recommended for future testing
- Accurate characterization of propeller aerodynamics is essential for modeling eVTOL aircraft
- DOE/RSM test techniques improve efficiency and data quality
- Propeller aerodynamics in transition are complex
- Split-plot designs accommodate practical testing considerations
- The identified models can be used for future eVTOL aircraft studies

Acknowledgments

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Questions – Thank you for your attention.

Related work presented at the AIAA AVIATION 2022 Forum

- Simmons, B. M., Morelli, E. A., Busan, R. C., Hatke, D. B., and O'Neal, A. W., "Aero-Propulsive Modeling for eVTOL Aircraft Using Wind Tunnel Testing with Multisine Inputs," *AIAA AVIATION 2022 Forum*, Jun. 2022.

Related propeller testing and modeling research

- Simmons, B. M., "System Identification for Propellers at High Incidence Angles," *Journal of Aircraft*, Vol. 58, No. 6, 2021, pp. 1336–1350.
- Simmons, B. M., and Hatke, D. B., "Investigation of High Incidence Angle Propeller Aerodynamics for Subscale eVTOL Aircraft," NASA TM-20210014010, May 2021.
- Stratton, M., and Landman, D., "Wind Tunnel Test and Empirical Modeling of Tilt-Rotor Performance for eVTOL Applications," *AIAA SciTech 2021 Forum*, AIAA Paper 2021-0834, Jan. 2021.