



System Identification for Propellers at High Incidence Angles

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AFM-11/TF-04: Design, Testing, and Modeling for the LA-8 Tilt-Wing VTOL Aircraft I

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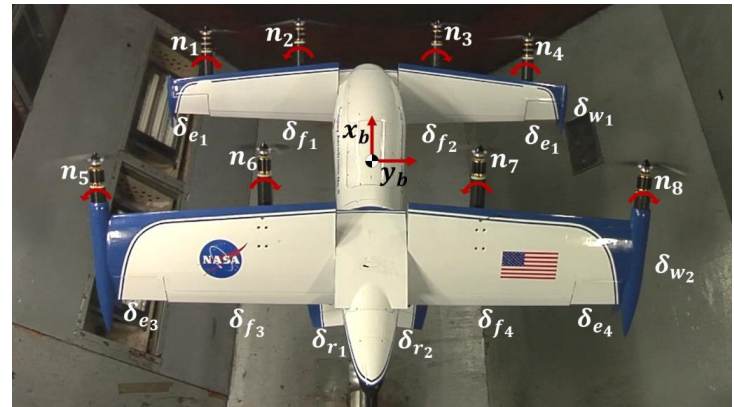
- Propellers used on eVTOL aircraft experience large incidence angles
- Sparse data or mathematical models exist for propellers at incidence

Objective: develop a propulsion model for the LA-8 aircraft for use in flight dynamics simulations

- Enhance understanding of eVTOL vehicle aerodynamics
- Improve simulation fidelity for the full-vehicle



LA-8 in the NASA Langley 12-Foot Low-Speed Tunnel.



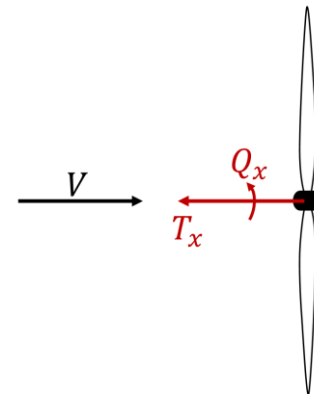
LA-8 propulsor and control surface definitions.

Axial Propeller Aerodynamics

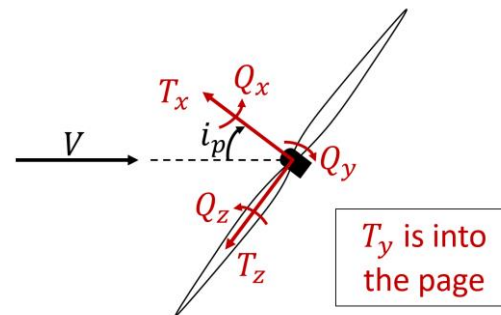
- Produces a thrust force T_x and aerodynamic torque Q_x about the axis of rotation
- Strong dependence on advance ratio $J = \frac{V}{nD}$ (and propeller geometry)
- May also be a function of blade Reynolds number Re and tip Mach number M_{tip}
- Thrust and torque coefficients are defined as:
 $C_{T_x} = T_x / \rho n^2 D^4$ and $C_{Q_x} = Q_x / \rho n^2 D^5$

Propeller Aerodynamics at Incidence

- Produces forces and moments in all axes, including T_y, T_z, Q_y, Q_z
- Additional strong dependence on incidence angle i_p
- Important for modeling eVTOL vehicles



Axial Propeller Forces and Moments.



Propeller Forces and Moments at Incidence.



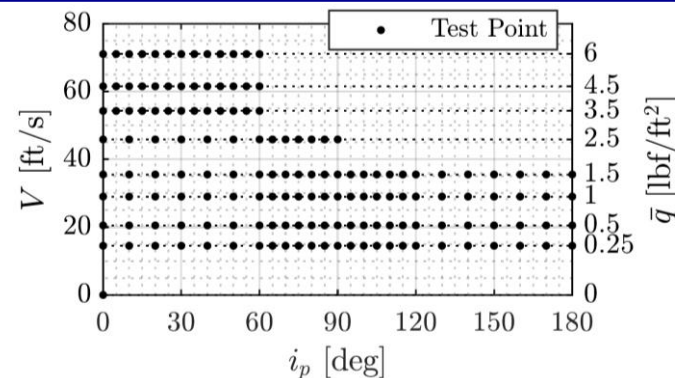
LA-8 Isolated Propeller Wind Tunnel Test



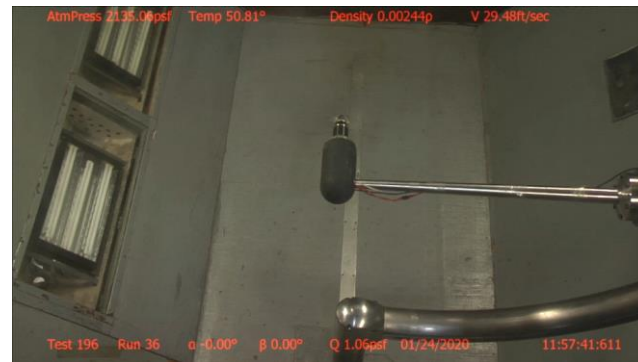
- LA-8 full-envelope static and dynamic testing for the CW and CCW propeller
- Test conditions
 - Incidence angle, i_p , ranging from 0° to 180°
 - Freestream airspeed from 0 to 71 ft/s (0-6 psf $\bar{q}$)
 - Motor speed ranging from 1500 to 6000 RPM
 - Re between 40,000 to 140,000

Further information:

Simmons, B. M., and Hatke, D. B., "Investigation of High Incidence Angle Propeller Aerodynamics for Subscale eVTOL Aircraft," NASA TM, 2021. To be published.



Static propeller designed test points.

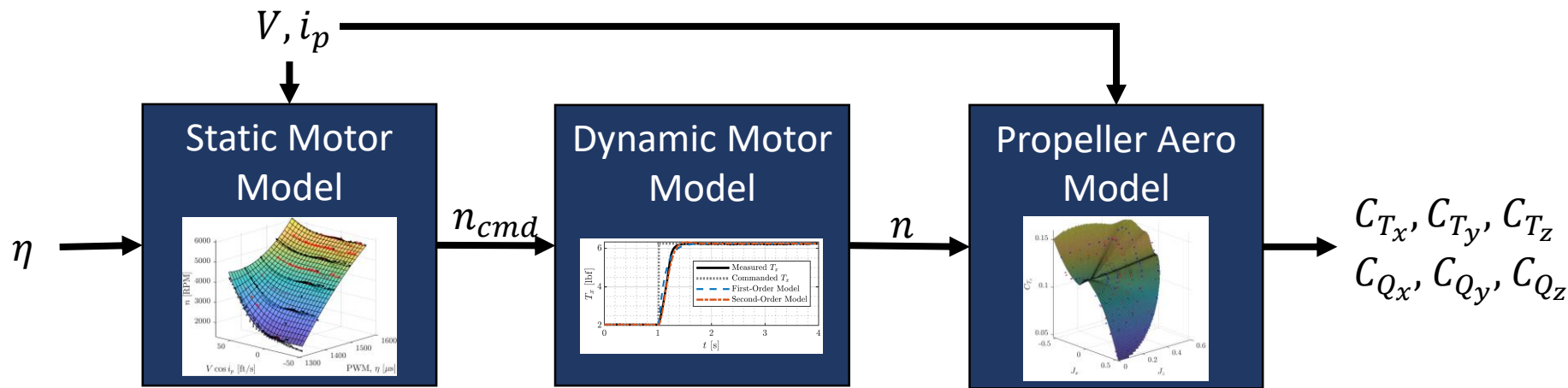


Isolated propeller wind tunnel run (x20 speed).

LA-8 Propulsion Model Overview

- The LA-8 propulsion model consists of
 - Static motor model ($\eta, V, i_p \rightarrow n_{cmd}$)
 - Dynamic motor model ($n_{cmd} \rightarrow n$)
 - Propeller aerodynamic model ($n, V, i_p \rightarrow C_{T_x}, C_{T_y}, C_{T_z}, C_{Q_x}, C_{Q_y}, C_{Q_z}$)
- Collectively relates controller commands to force and moment output

η – PWM throttle command
 n_{cmd} – commanded propeller speed
 n – actual propeller rotational speed



LA-8 propulsion modeling approach.

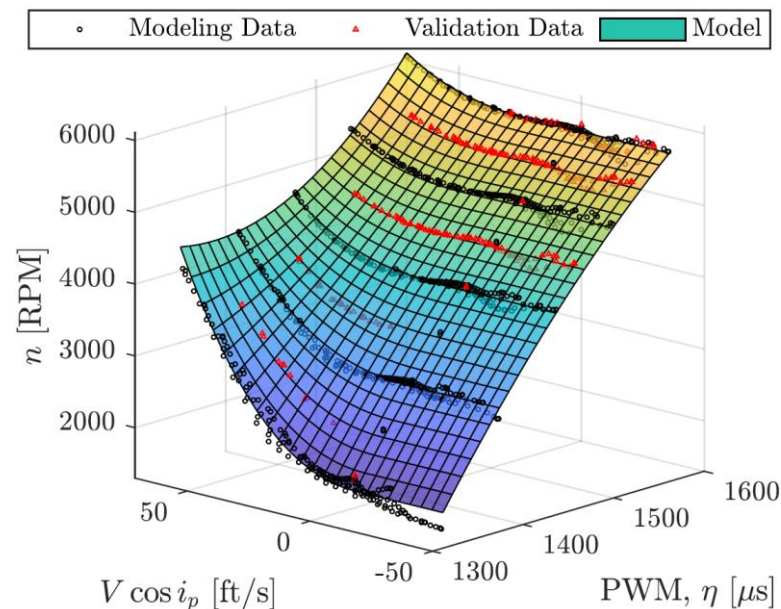
- Model relating PWM throttle commands (η) to propeller speed command (n_{cmd})
- Model identified using multivariate orthogonal function (MOF) modeling
- Explanatory variables:

$$\hat{\eta} = \eta - 1475$$

$$V_{x^+} = \begin{cases} V \cos i_p & 0^\circ \leq i_p \leq 90^\circ \\ 0 & 90^\circ < i_p \leq 180^\circ \end{cases}$$

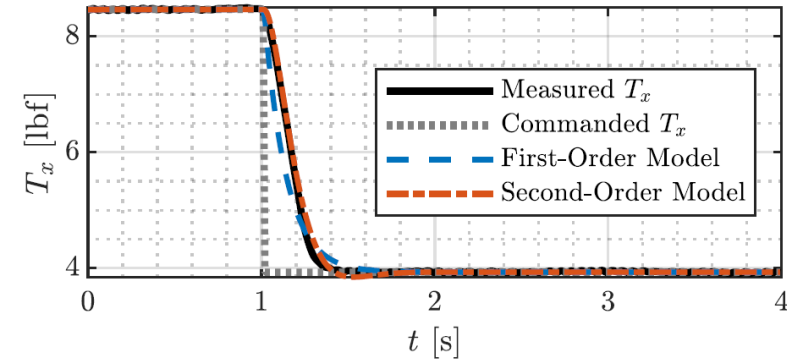
- Identified CW model structure:

$$n = n_o + n_{\hat{\eta}} \hat{\eta} + n_{V_{x^+}^3} V_{x^+}^3 + n_{\hat{\eta} V_{x^+}^2} \hat{\eta} V_{x^+}^2 + n_{\hat{\eta}^2 V_{x^+}^2} \hat{\eta}^2 V_{x^+}^2 + n_{\hat{\eta}^2} \hat{\eta}^2$$

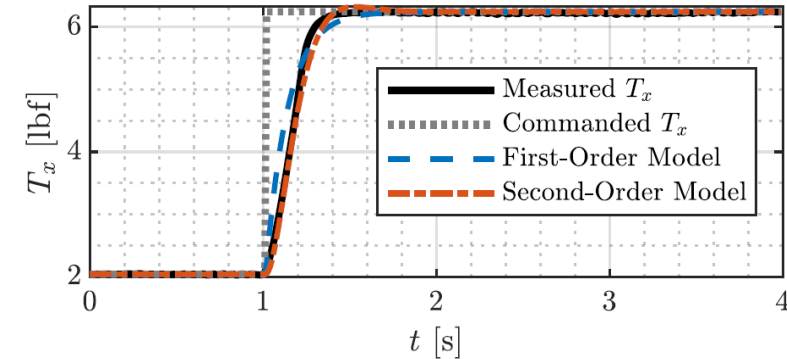


Static motor model response surface.

- Model of motor/ESC dynamic response
- Relates commanded motor speed (n_{cmd}) to actual motor speed (n)
- Model structure consists of first-order or second-order lag dynamics:
 - $\dot{n} = \frac{1}{\tau}(n_{cmd} - n)$
 - $\ddot{n} + 2\zeta\omega_n \dot{n} + \omega_n^2 n = \omega_n^2 n_{cmd}$
- Parameter estimates (τ, ζ, ω_n) identified using time-domain output-error method
- Models fit to wind tunnel data with throttle step inputs excitations
- Increasing or decreasing motor speed has a different dynamic response



Models for decreasing motor speed.



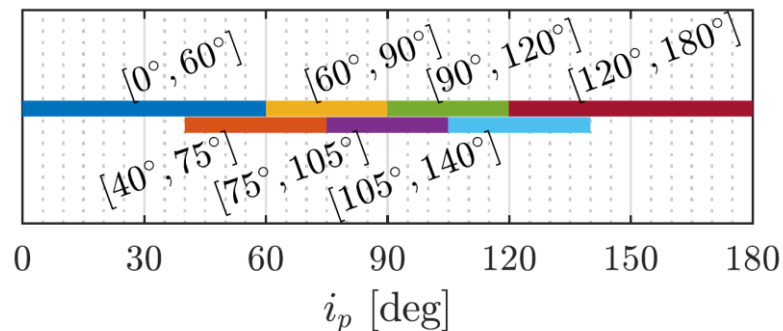
Models for increasing motor speed.

- Nonlinear polynomial models covering the full LA-8 “wind tunnel envelope”
- Partitioned models covering a range of incidence angles
- Models identified using MOF modeling
- Response variables, propeller force and moment coefficients:

$$\begin{aligned} \blacksquare C_{T_x} &= \frac{T_x}{\rho n^2 D^4}, C_{T_y} = \frac{T_y}{\rho n^2 D^4}, C_{T_z} = \frac{T_z}{\rho n^2 D^4} \\ \blacksquare C_{Q_x} &= \frac{Q_x}{\rho n^2 D^5}, C_{Q_y} = \frac{Q_y}{\rho n^2 D^5}, C_{Q_z} = \frac{Q_z}{\rho n^2 D^5} \end{aligned}$$

- Explanatory variables, normal J , tangential J , and Reynolds number:

$$\begin{aligned} \blacksquare J_x &= \frac{V \cos i_p}{n D} \\ \blacksquare J_z &= \frac{V \sin i_p}{n D} \\ \blacksquare \widehat{Re}_p &= \frac{Re-10^5}{10^5} \text{ where } Re = \frac{\rho(0.75 \pi n D)c}{\mu} \end{aligned}$$



Incidence angle partitions for the LA-8 propeller aerodynamic model.



Propeller Aerodynamic Model Results



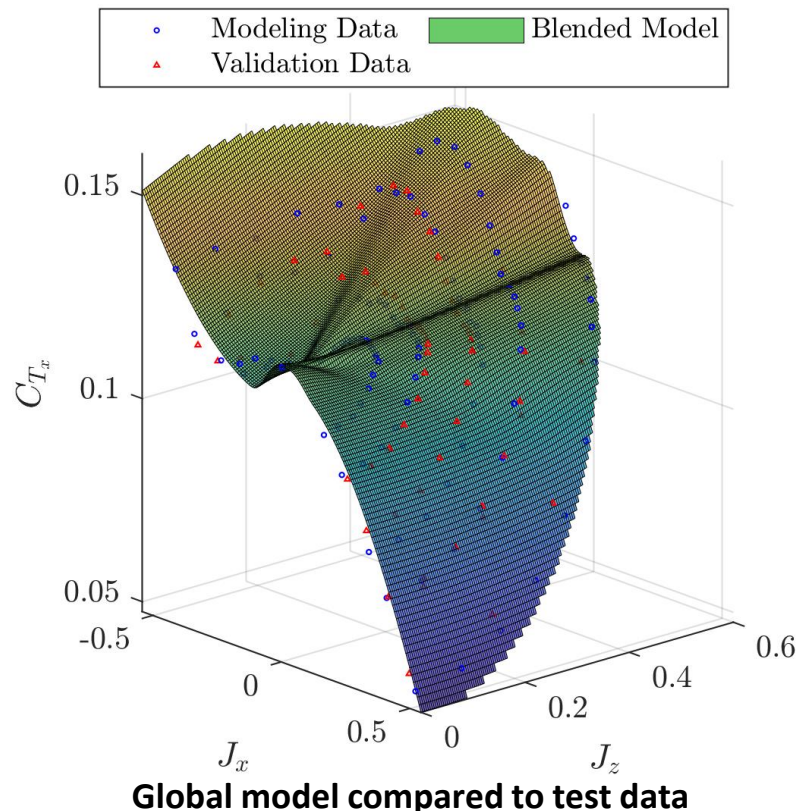
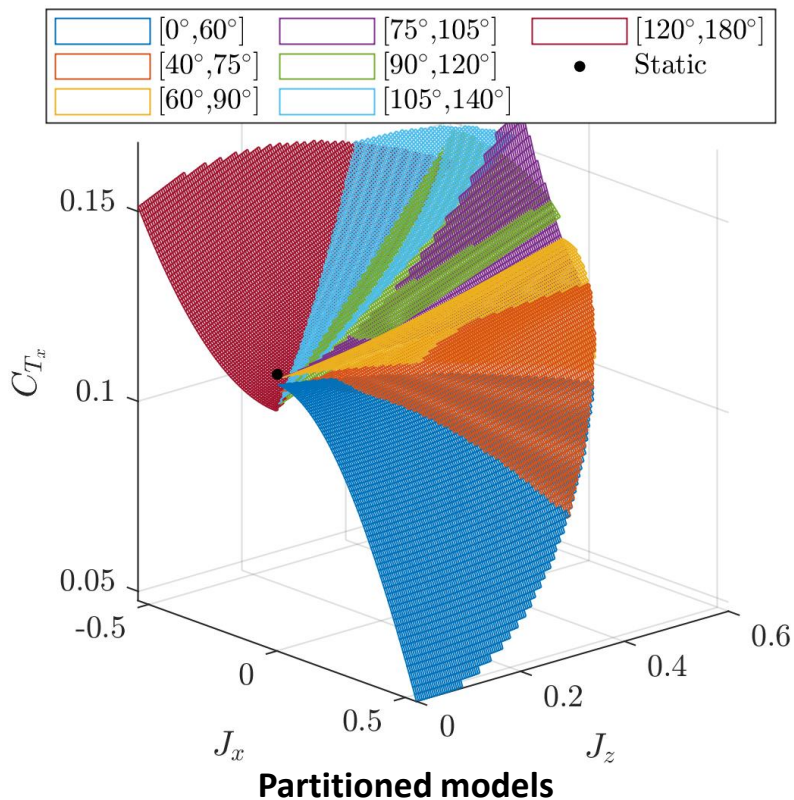
- C_{T_x} and C_{Q_x} have the best modeling fit and prediction capability
- C_{T_z} , C_{Q_y} , and C_{Q_z} generally have a quality modeling fit and good prediction capability
- C_{T_y} generally had the highest modeling error and prediction error
- Dominant responses have modeling and prediction errors generally well below 5%
- Weaker responses have modeling and prediction errors generally less than 10%

Polynomial model terms for the clockwise propeller model on $0^\circ \leq i_p \leq 60^\circ$

Response	Model Terms
C_{T_x}	bias, J_x^2 , J_z^2 , $\hat{R}e^3$, J_x^3
C_{T_y}	J_z , $J_x J_z$, $J_x^2 J_z$, $J_z \hat{R}e^2$, $J_z \hat{R}e$, $J_x J_z \hat{R}e$, J_z^3
C_{T_z}	J_z , J_z^3 , $J_x J_z$
C_{Q_x}	bias, J_x^2 , $J_x J_z^2$, J_x , $J_x \hat{R}e$
C_{Q_y}	$J_x J_z$, $J_x J_z \hat{R}e$, J_z , J_z^3 , $J_z \hat{R}e$, $J_z \hat{R}e^2$
C_{Q_z}	J_z , $J_x J_z \hat{R}e$, $J_x^2 J_z$, $J_z \hat{R}e$, $J_x J_z$



Global Propeller Aerodynamic Model Blending



Global model blending for C_{T_x} at a propeller blade Reynolds number of 100,000.



Conclusions



- An accurate propulsion model is crucial to modeling eVTOL vehicles
- A propulsion model consisting of a static motor model, dynamic motor model, and propeller aerodynamic model proved successful for flight dynamics simulations
- Propeller aerodynamics have a strong, nonlinear dependence on incidence angle
- Propeller aerodynamics were best described by several local models partitioned by incidence angle and as a function of J_x , J_z , and Re
- The identified propeller models have good predictive capability and small fit error



Questions – Thank you for your attention.



Acknowledgments

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Design, Testing, and Modeling for the LA-8 Tilt-Wing VTOL Aircraft I & II References

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2. Busan, R. C., Murphy, P. C., Hatke, D. B., and Simmons, B. M., “Wind Tunnel Testing Techniques for a Tandem Tilt-Wing, Distributed Electric Propulsion VTOL Aircraft”
3. **Simmons, B. M., “System Identification for Propellers at High Incidence Angles”**
4. Geuther, S. C., and Fei, X., “LA-8 Computational Analysis and Validation Studies Using FlightStream”
5. Simmons, B. M., and Murphy, P. C., “Wind Tunnel-Based Aerodynamic Model Identification for a Tilt-Wing, Distributed Electric Propulsion Aircraft”
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