System Identification for eVTOL Aircraft Using Simulated Flight Data

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- LA-8 background
- Modeling strategy
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LA-8 flight test.

The input design, signal processing, and parameter estimation methods used for this work were from the SIDPAC software toolbox: https://software.nasa.gov/software/LAR-16100-1

Research Motivation

- Electric vertical takeoff and landing (eVTOL) aircraft enabling Urban Air Mobility (UAM) are gaining significant interest
- Investigate system identification methods for eVTOL vehicles
- Simulation-based analysis to refine methods for future flight testing
- eVTOL aircraft modeling challenges
  - Many control surfaces and propulsors
  - Significant aero-propulsive interactions
  - Large changes in aerodynamics
  - Vehicle instability
  - Characteristics of both fixed-wing and rotary-wing aircraft
  - Different configurations (tilt-wing, tilt-rotor, etc.) require different strategies

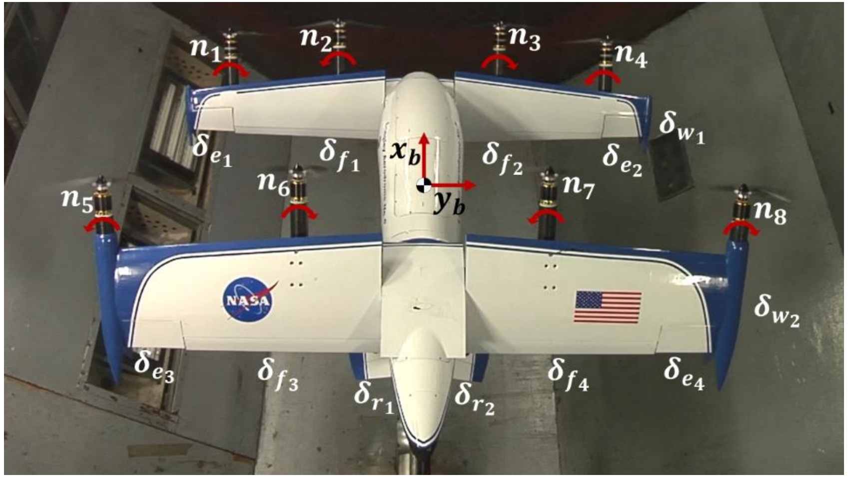
LA-8 eVTOL Testbed and Simulation

LA-8 research vehicle[1]

- Tandem tilt-wing, DEP, VTOL configuration
- 63 lbs, 6 ft wingspan
- 20 available control effectors

LA-8 aircraft flight dynamics simulation

- Generalized UAM-class vehicle simulation[2]
- Nonlinear LA-8 aero-propulsive model[3]
- Robust Uniform Control Approach[4]



LA-8 control effector definitions.

1. North, D. D., Howland, G., and Busan, R. C., “Design and Fabrication of the Langley Aerodrome No. 8 Distributed Electric Propulsion VTOL Testbed,” *AIAA SciTech 2021 Forum*, AIAA Paper 2021-1188.
2. Gregory, I. M. et al., “Intelligent Contingency Management for Urban Air Mobility,” *AIAA SciTech 2021 Forum*, AIAA Paper 2021-1000.
3. Simmons, B. M., and Murphy, P. C., “Wind Tunnel-Based Aerodynamic Model Identification for a Tilt-Wing, Distributed Electric Propulsion Aircraft,” *AIAA SciTech 2021 Forum*, AIAA Paper 2021-1298.
4. Cook, J., and Gregory, I., “A Robust Uniform Control Approach for VTOL Aircraft,” *VFS Autonomous VTOL Technical Meeting and Electric VTOL Symposium*, Jan. 2021.

Modeling Approach Overview

- Combination of fixed-wing and rotary-wing system identification
- Informed by vehicle attributes and previous modeling experience[1,2]
- Model of aero-propulsive forces and moments exerted on the aircraft as a function of vehicle state and control variables
- Equation-error method in the frequency domain[3,4,5]
- Point models identified at reference flight conditions: $u, \delta_{w_1}, \delta_{w_2}, h \text{ (or } \rho)$

1. Simmons, B. M., and Murphy, P. C., "Wind Tunnel-Based Aerodynamic Model Identification for a Tilt-Wing, Distributed Electric Propulsion Aircraft," *AIAA SciTech 2021 Forum*, AIAA Paper 2021-1298.
2. Simmons, B. M., Buning, P. G., and Murphy, P. C., "Full-Envelope Aero-Propulsive Model Identification for Lift+Cruise Aircraft Using Computational Experiments," *AIAA AVIATION 2021 Forum*, AIAA Paper 2021-3170.
3. Morelli, E. A., and Klein, V., *Aircraft System Identification: Theory and Practice*, 2nd ed., Sunflyte Enterprises, Williamsburg, VA, 2016.
4. Klein, V., "Aircraft Parameter Estimation in Frequency Domain," *4th Atmospheric Flight Mechanics Conference*, AIAA Paper 1978-1344.
5. Morelli, E. A., "Autonomous Real-Time Global Aerodynamic Modeling in the Frequency Domain," *AIAA SciTech 2020 Forum*, AIAA Paper 2020-0761.

Response Variables

- Aero-propulsive forces and moments are the response variables
- Not measured in flight – must be inferred from other measurements
- Applied forces:

$$X = ma_x, \quad Y = ma_y, \quad Z = ma_z$$

- Applied moments (accounting for propulsor gyroscopic effects):

$$L = I_x\dot{p} - I_{xz}\dot{r} + (I_z - I_y)qr - I_{xz}pq + \dot{h}_x + qh_z - rh_y$$

$$M = I_y\dot{q} + (I_x - I_z)pr + I_{xz}(p^2 - r^2) + \dot{h}_y + rh_x - ph_z$$

$$N = I_z\dot{r} - I_{xz}\dot{p} + (I_y - I_x)pq + I_{xz}qr + \dot{h}_z + ph_y - qh_x$$

Explanatory Variables

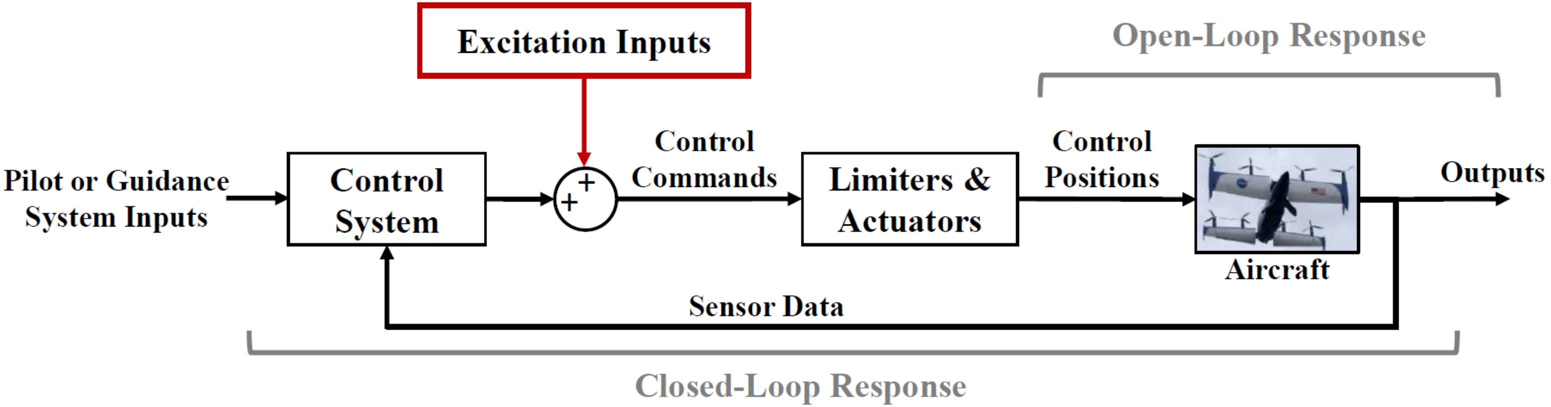
- Longitudinal states: u, w, q
- Lateral-directional states: v, p, r
- Control surface deflections: $\delta_{e_1}, \delta_{e_2}, \delta_{e_3}, \delta_{e_4}, \delta_{f_1}, \delta_{f_2}, \delta_{f_3}, \delta_{f_4}, \delta_{r_1}, \delta_{r_2}$
- Propeller rotational speed: $n_1, n_2, n_3, n_4, n_5, n_6, n_7, n_8$
- Sample model structure:

$$
\begin{aligned}
Z = {} & Z_u u + Z_w w + Z_q q + Z_{\delta_{e_1}} \delta_{e_1} + Z_{\delta_{e_2}} \delta_{e_2} + Z_{\delta_{e_3}} \delta_{e_3} + Z_{\delta_{e_4}} \delta_{e_4} + Z_{\delta_{f_1}} \delta_{f_1} + \ldots \\
& + Z_{\delta_{f_2}} \delta_{f_2} + Z_{\delta_{f_3}} \delta_{f_3} + Z_{\delta_{f_4}} \delta_{f_4} + Z_{\delta_{r_1}} \delta_{r_1} + Z_{\delta_{r_2}} \delta_{r_2} + Z_{n_1} n_1 + Z_{n_2} n_2 + \ldots \\
& + Z_{n_3} n_3 + Z_{n_4} n_4 + Z_{n_5} n_5 + Z_{n_6} n_6 + Z_{n_7} n_7 + Z_{n_8} n_8 + Z_o
\end{aligned}
$$

- The method can be extended to nonlinear model identification

Experimental Design Approach

- **Goal:** generate informative flight data for model identification
- Multiple-input excitation required for efficient testing
- Vehicle instability requires use of feedback control during testing
- Instrumentation requirements follow research quality aircraft testing



Proper application of excitation inputs relative to the control system.[1]

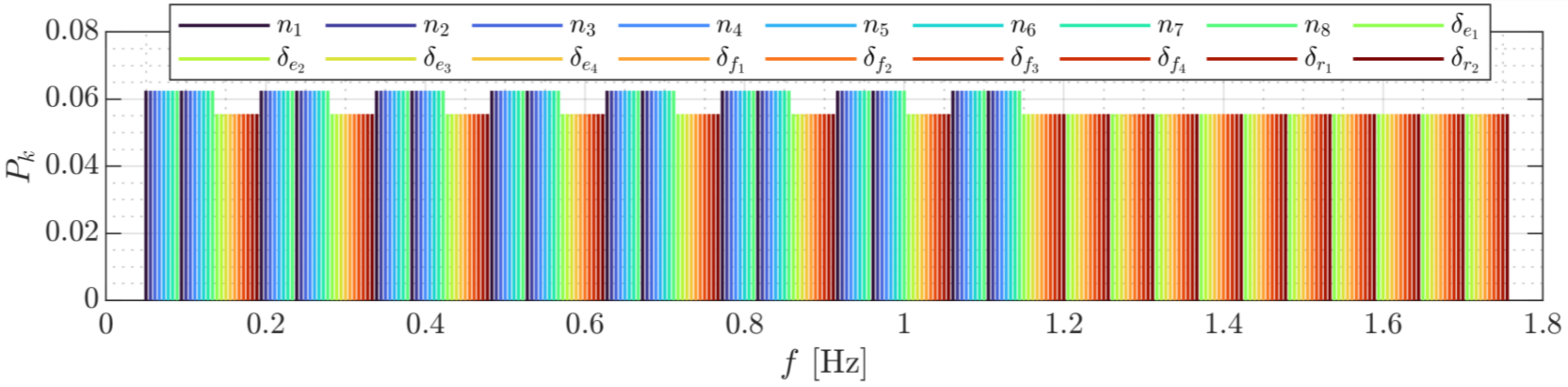
1. Morelli, E. A., and Klein, V., *Aircraft System Identification: Theory and Practice*, 2nd ed., Sunflyte Enterprises, Williamsburg, VA, 2016.

Input Design

- Orthogonal phase-optimized multisine inputs[1,2,3]
- Unique signal for each LA-8 control effector
- More input design details are given in the paper

$$\boldsymbol{u_j} = \sum_{k \in K_j} A\sqrt{P_k}\sin\left(\frac{2\pi k \boldsymbol{t}}{T} + \phi_k\right)$$

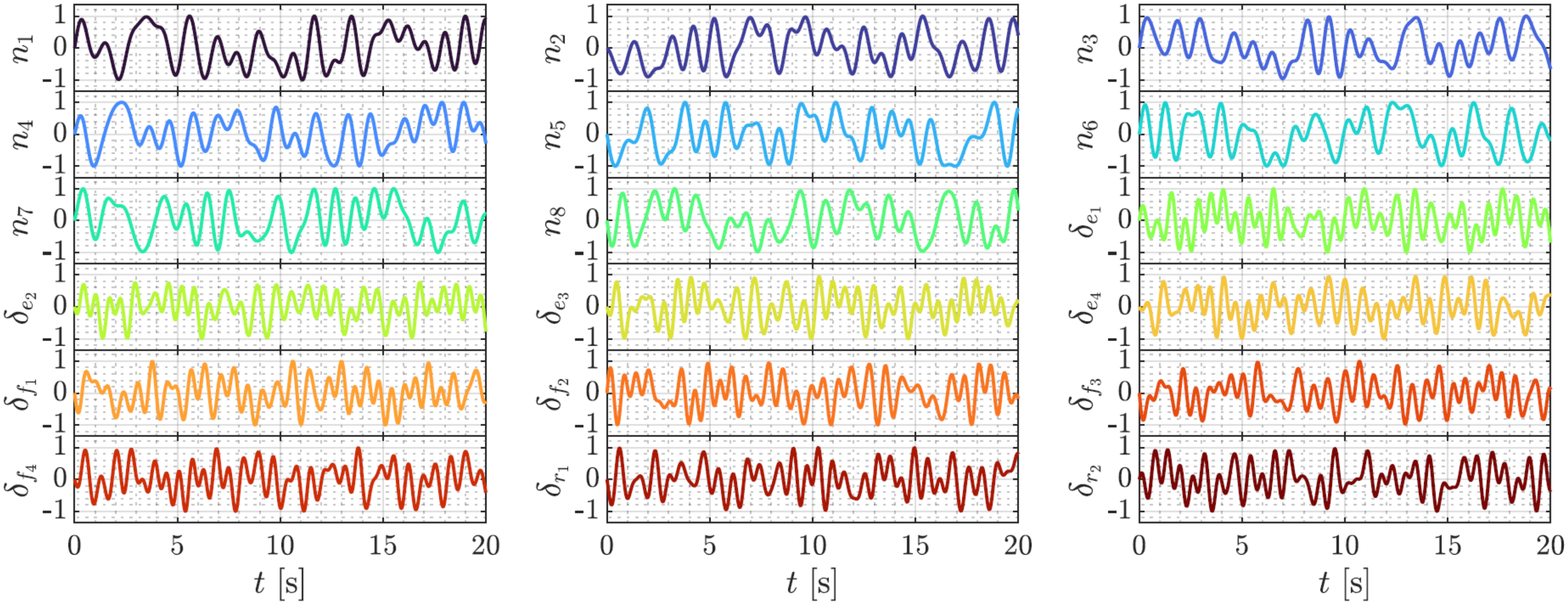
$\boldsymbol{u_j}$ – jth multisine signal
A – signal amplitude
P_k – kth power fraction
T – fundamental period
ϕ_k – kth phase angle



LA-8 aircraft multisine input spectra for each control effector.

1. Morelli, E. A., "Multiple Input Design for Real-Time Parameter Estimation in the Frequency Domain," *13th IFAC Conference on System Identification*, Aug. 2003.
2. Morelli, E. A., and Klein, V., *Aircraft System Identification: Theory and Practice*, 2nd ed., Sunflyte Enterprises, Williamsburg, VA, 2016.
3. Morelli, E. A., "Practical Aspects of Multiple-Input Design for Aircraft System Identification Flight Tests," *AIAA AVIATION 2021 Forum*, AIAA Paper 2021-2795.

LA-8 Multisine Signals

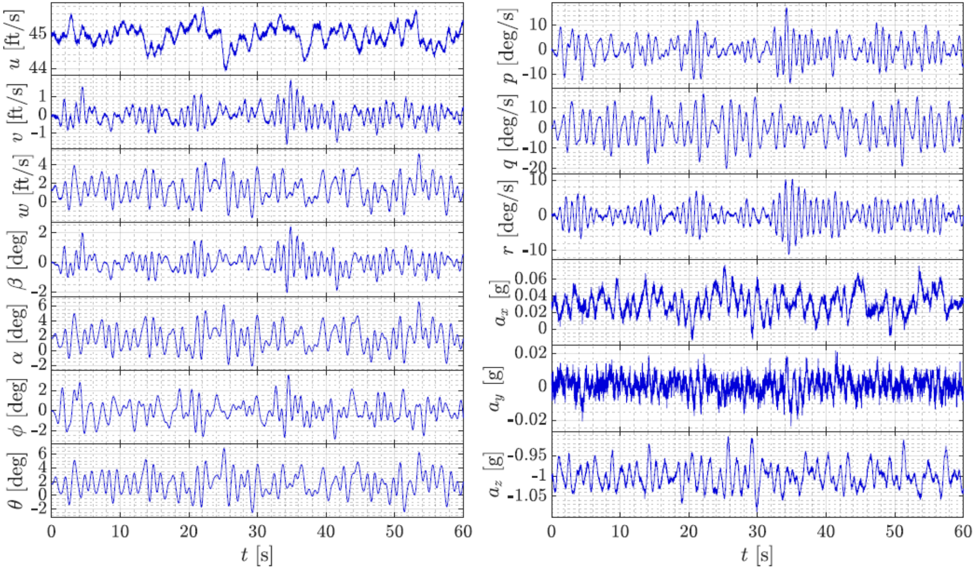


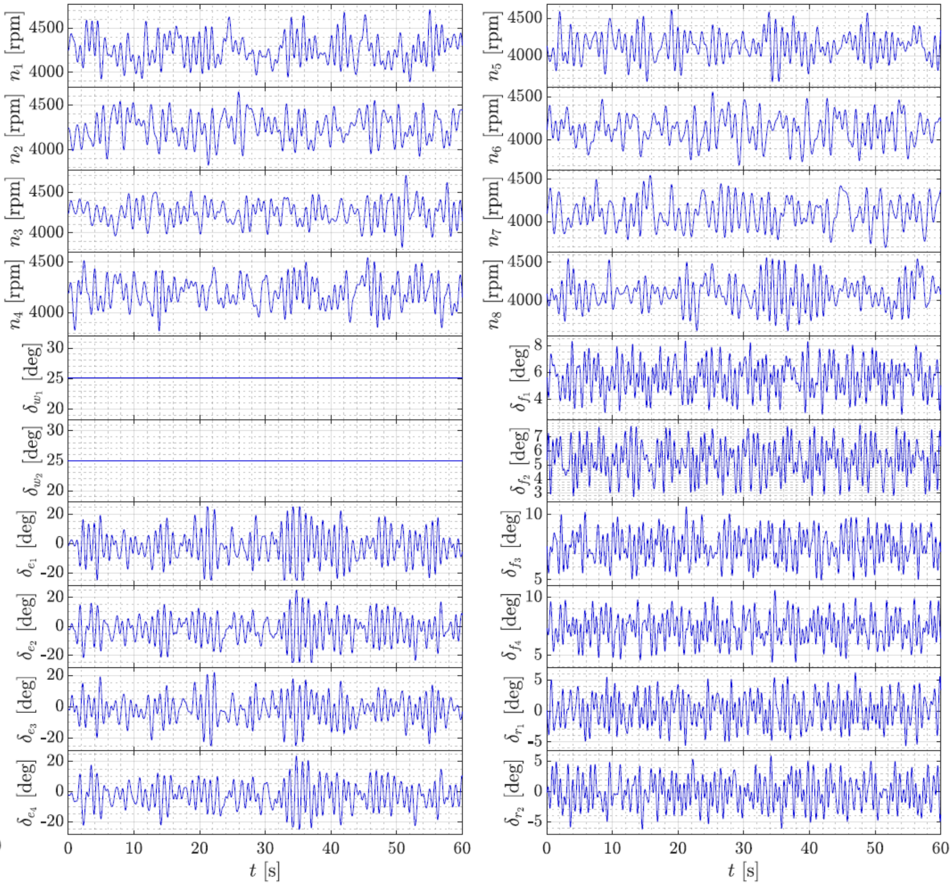
LA-8 aircraft normalized multisine inputs used for system identification.

Simulated LA-8 Flight Data ($u = 45$ ft/s)

- 60-second multisine maneuver
- Simulated flight data corrupted with measurement noise[1]

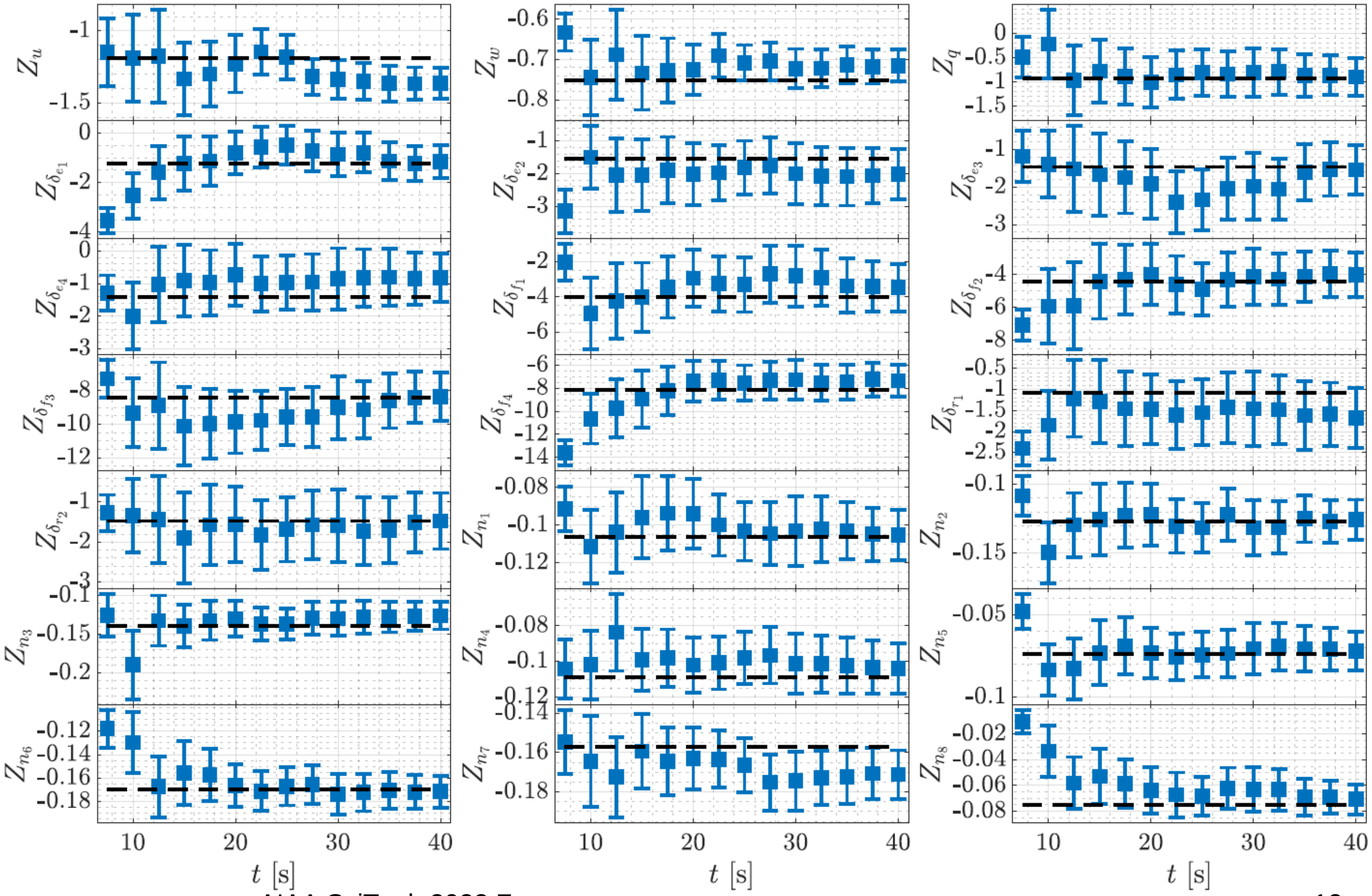
1. Morelli, E. A., Cunningham, K., and Hill, M. A., “Global Aerodynamic Modeling for Stall/Upset Recovery Training Using Efficient Piloted Flight Test Techniques,” *AIAA Modeling and Simulation Technologies (MST) Conference*, AIAA Paper 2013-4976.



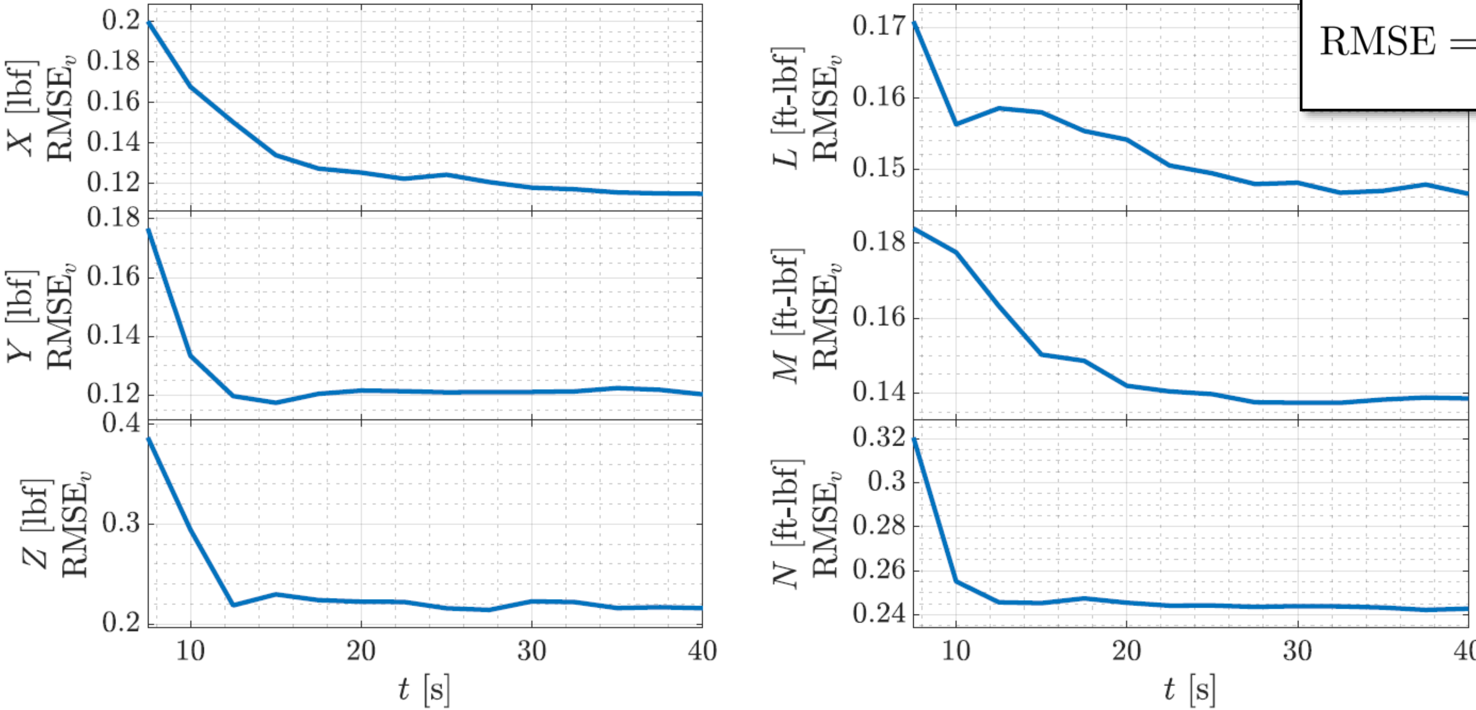


Z Parameters Against Time ($u = 45$ ft/s)

- Model parameters against maneuver length are shown
- Parameters appear to converge within 40 seconds
- Similar results obtained for other responses



Prediction Error Against Time ($u = 45$ ft/s)



$$\text{RMSE} = \sqrt{\frac{(\boldsymbol{z} - \hat{\boldsymbol{y}})^T (\boldsymbol{z} - \hat{\boldsymbol{y}})}{N}}$$

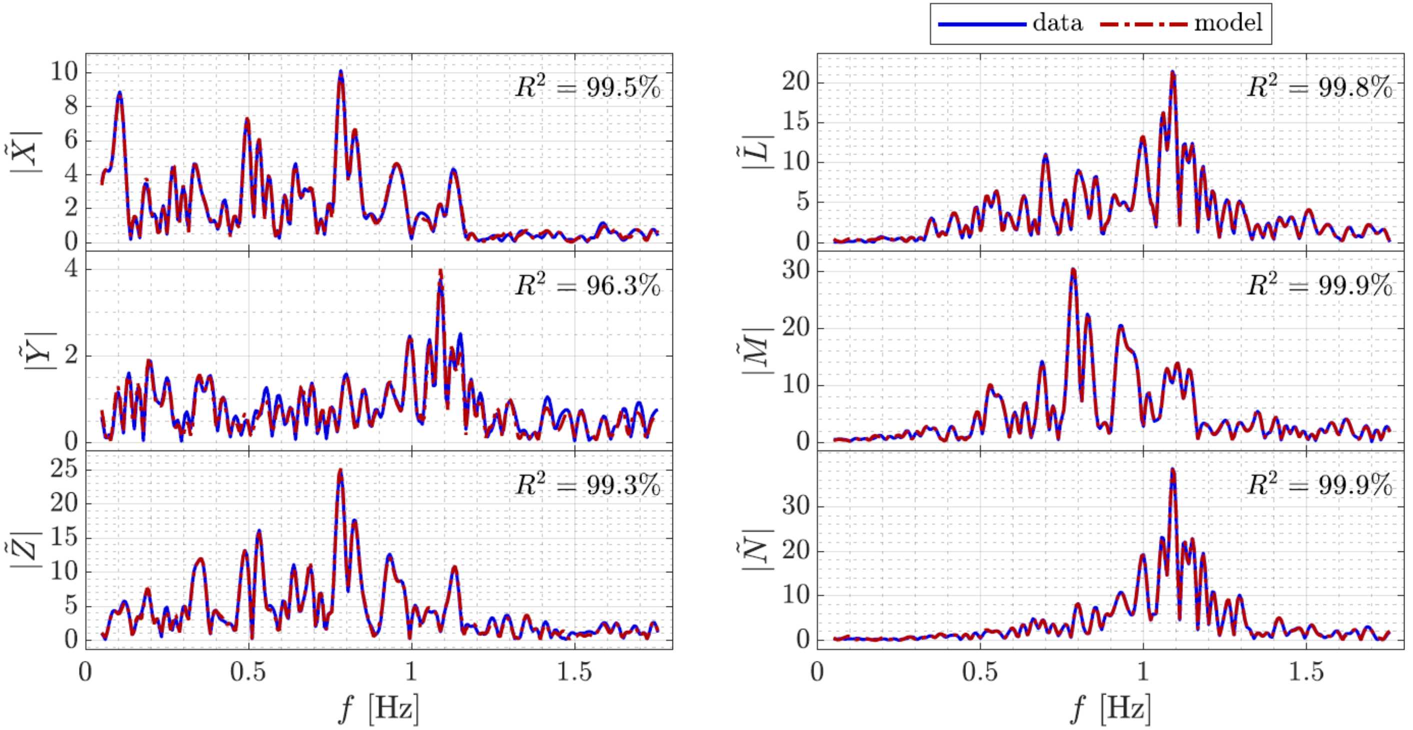
$\boldsymbol{z}$ – measured response
$\hat{\boldsymbol{y}}$ - modeled response
N – number of data points

<u>Limited benefit beyond 40 s</u>

Variation of validation RMSE with maneuver time used for modeling.

Local Modeling Results ($u = 45$ ft/s)

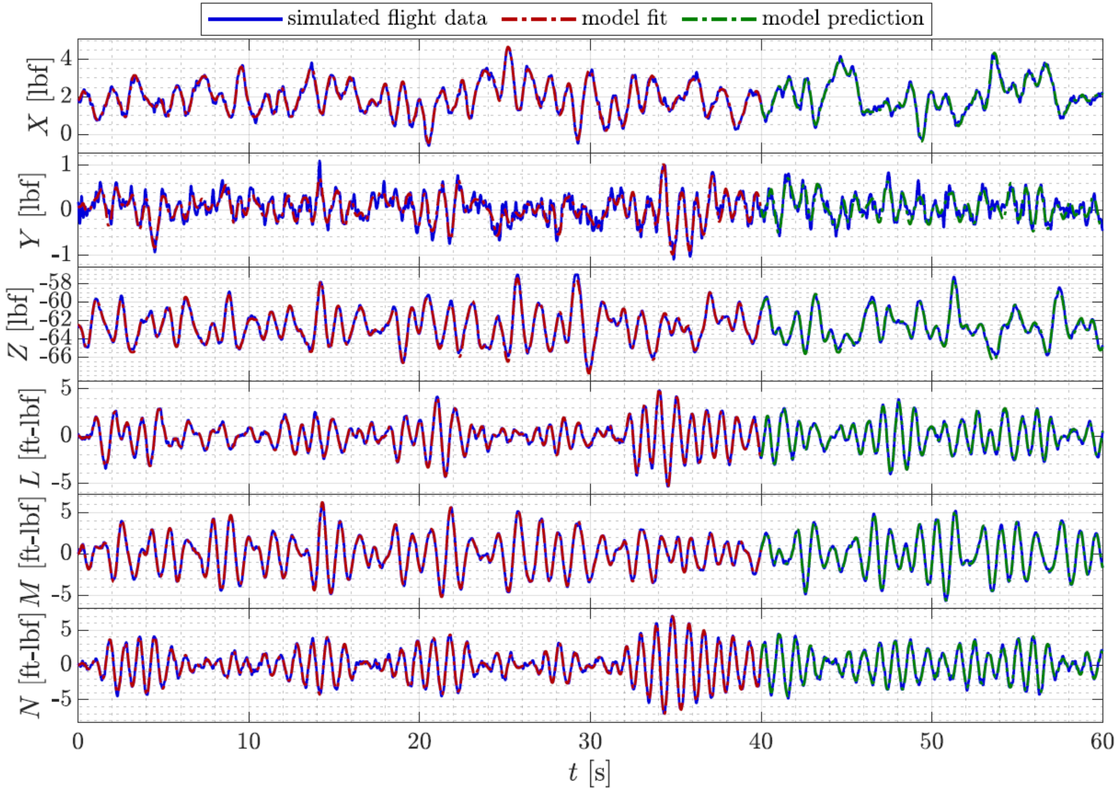
- Model computed using complex least-squares regression
- Good model fit
- High R^2 value
- Similar results obtained across the flight envelope



Comparison of modeling response data and model fit in the frequency domain.

Local Modeling Results ($u = 45$ ft/s)

- Time-domain comparison of the model fit and model prediction to smoothed responses
- Good model fit
- Good prediction capability
- Results were similar for the other flight conditions across the flight envelope
- Additional global modeling results are shown in the paper



Model fit and model prediction in the time domain for a simulated LA-8 maneuver.

Concluding Remarks

- eVTOL aircraft present new system identification challenges
- A modeling approach for eVTOL aircraft was developed
- Orthogonal phase-optimized multisine inputs are needed for efficient testing and accurate aero-propulsive characterization
- Identified models have good predictive capability and agreement with linearized simulation parameters
- The presented flight test and modeling techniques can be applied for many current and future vehicles

Acknowledgments

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- LA-8 flight control system development/integration: Jacob Cook
- Vehicle simulation development support: Thomas Britton
- System identification advice: Eugene Morelli

Questions – Thank you for your attention.

Related eVTOL Aircraft Modeling Research

- Simmons, B. M., and Murphy, P. C., "Wind Tunnel-Based Aerodynamic Model Identification for a Tilt-Wing, Distributed Electric Propulsion Aircraft," *AIAA SciTech 2021 Forum*, AIAA Paper 2021-1298.
- Simmons, B. M., Buning, P. G., and Murphy, P. C., "Full-Envelope Aero-Propulsive Model Identification for Lift+Cruise Aircraft Using Computational Experiments," *AIAA AVIATION 2021 Forum*, AIAA Paper 2021-3170.

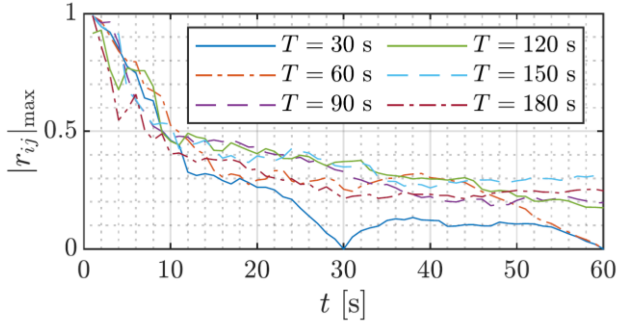
LA-8 wind tunnel test.

LA-8 flight test.

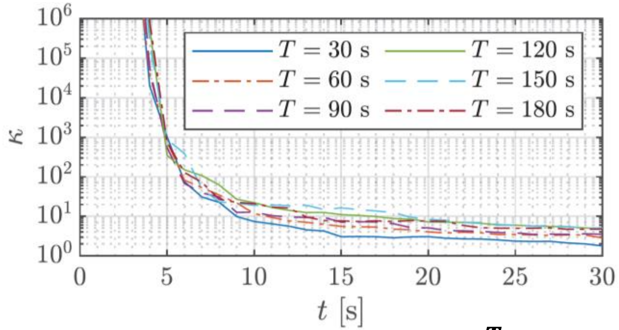
Backup Slides

Input Design Strategy

- Multiple-input orthogonal phase-optimized multisine signals[1]
- Individual multisine signals generated for each LA-8 effector (18 total)
- Overall frequency range was set to between 0.05 Hz and 1.8 Hz
- Propulsor harmonic components focused into lower frequencies
- Multiple designs considered by varying the fundamental period T
- A larger number of frequency components has been shown to improve modeling results[2]



Maximum input correlation coefficient.

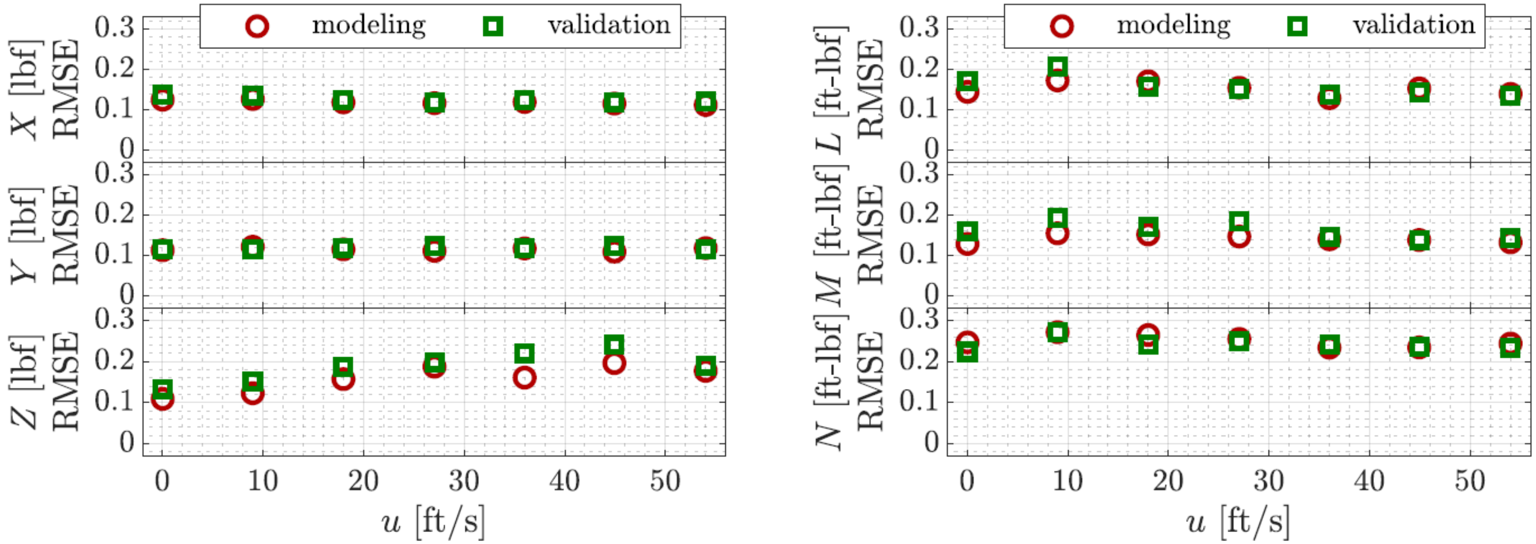


Condition number of $U^T U$.

1. Morelli, E. A., “Multiple Input Design for Real-Time Parameter Estimation in the Frequency Domain,” *13th IFAC Conference on System Identification*, Aug. 2003.
2. Morelli, E. A., and Smith, M. S., “Real-Time Dynamic Modeling: Data Information Requirements and Flight-Test Results,” *Journal of Aircraft*, Vol. 46, No. 6, 2009, pp. 1894–1905.

Global Modeling and Prediction Error

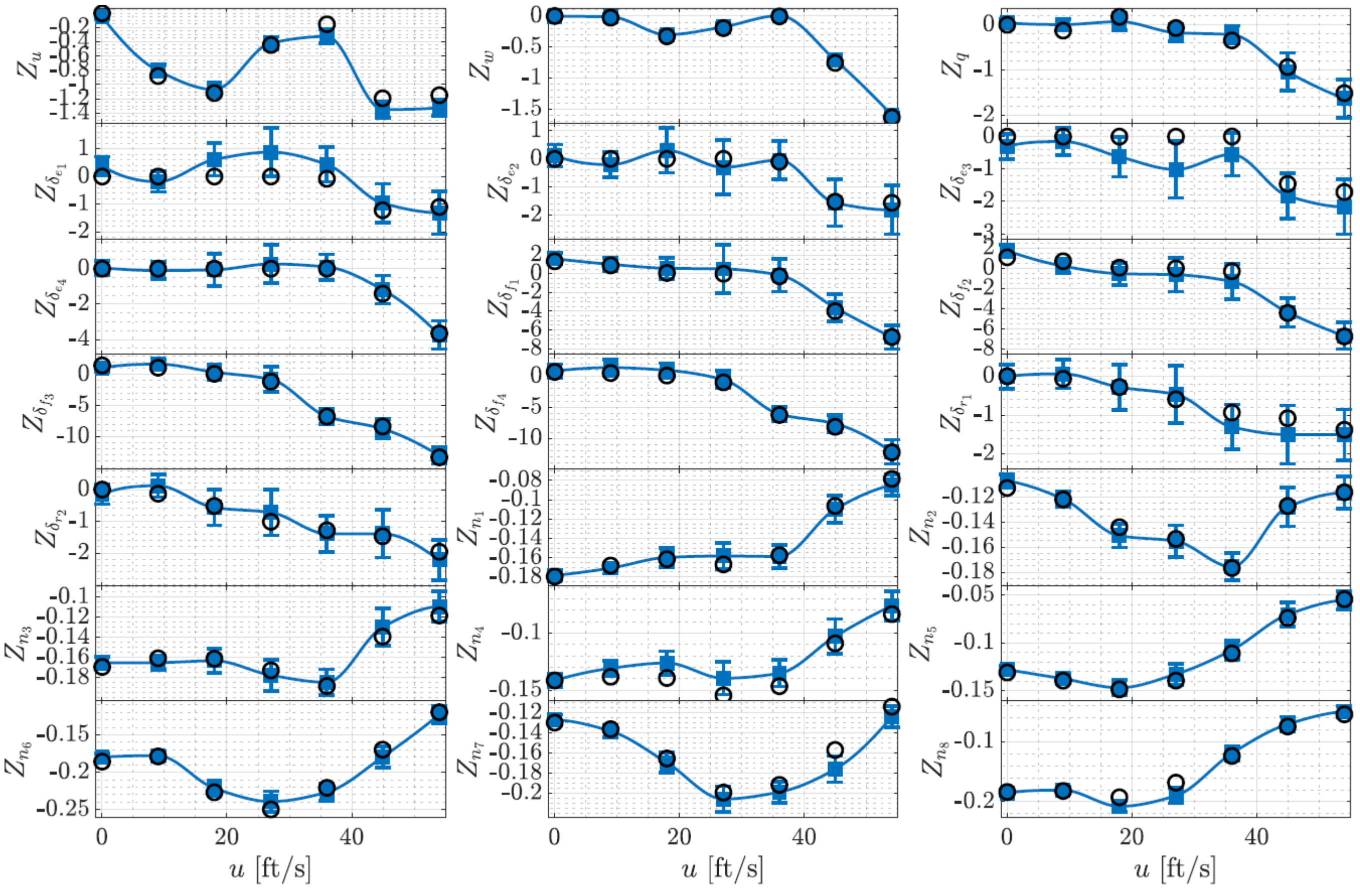
- Local models developed at several flight conditions
- The modeling and validation RMSE values are similar
- Additional global modeling results are shown in the paper

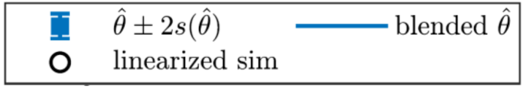


Modeling and validation RMSE for each response against reference u.

Global Z Parameter Estimates

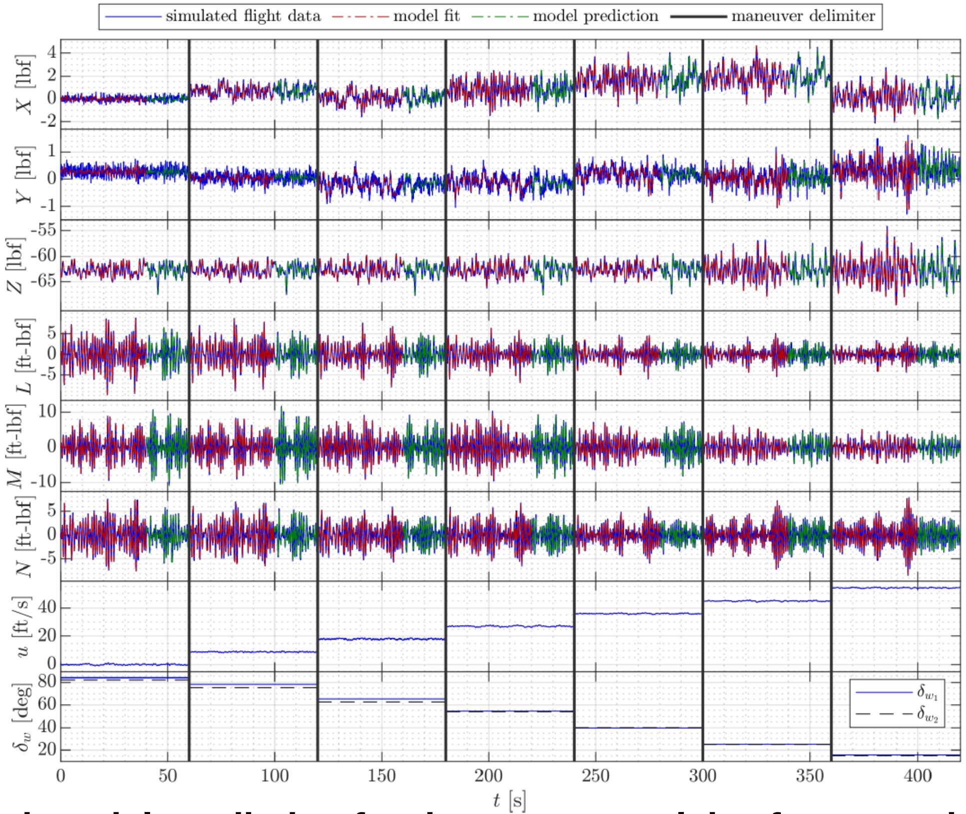
- Models identified using complex least-squares regression at each flight condition
- Parameters are blended using shape-preserving piecewise cubic interpolation
- The identified parameters agree well with linearized simulation parameters
- Similar results obtained for other responses





Global Modeling Results

- Data from a 60-second multisine maneuver were used to develop and validate a local model at several flight conditions
- A good model fit and good model prediction capability are observed for each flight condition



Model fit and model prediction for the aero-propulsive forces and moments at several reference conditions throughout the LA-8 transition envelope.