System Identification for a Subscale Tiltrotor eVTOL Aircraft from Hover Flight-Test Data

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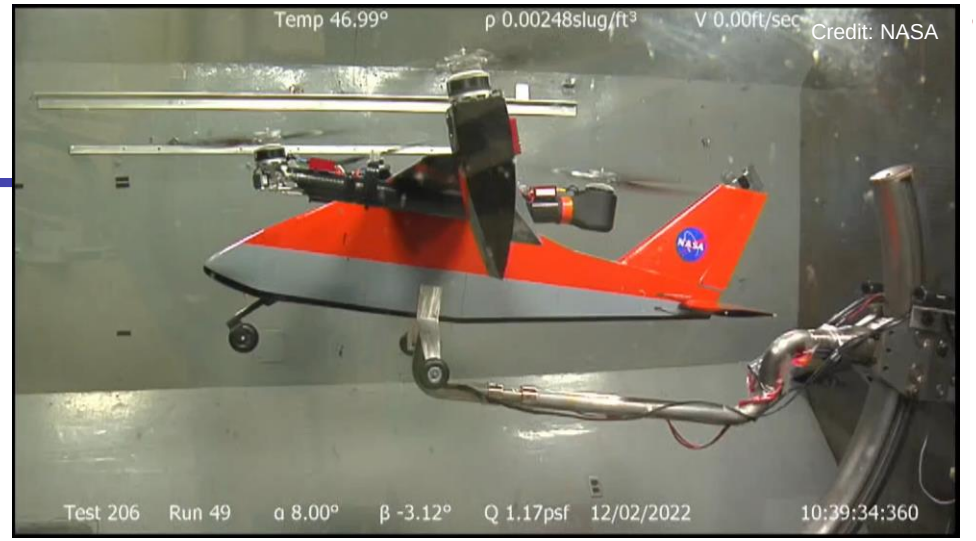
- Research motivation
- RAVEN-SWFT vehicle
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- Modeling approach and results
- Concluding remarks
- Questions/discussion



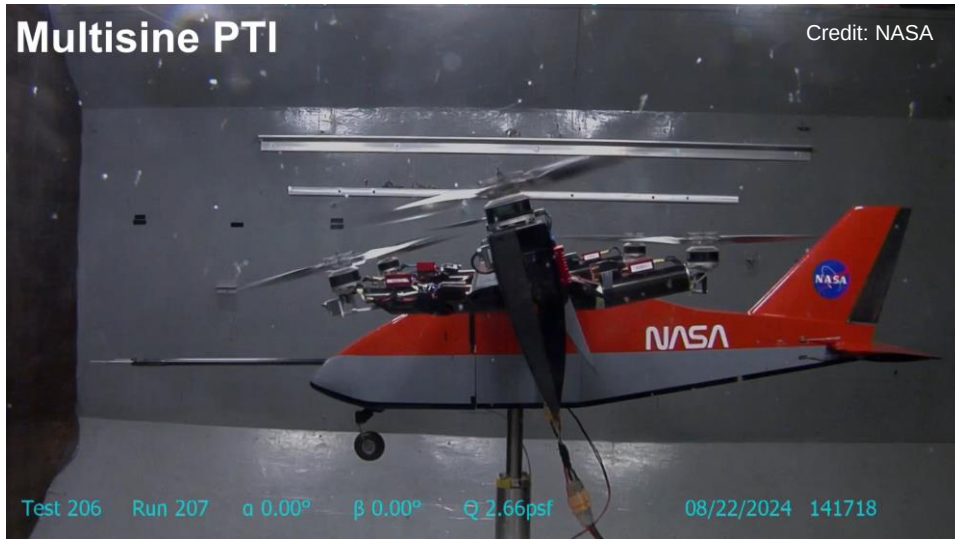


Research Motivation

- Technology advances enabling Advanced Air Mobility (AAM) vehicles and missions
  - VTOL, STOL, and CTOL configurations
  - Many control surfaces and propulsors
  - Significant propulsion-airframe interactions
- Multidisciplinary need for flight simulations driven by high-fidelity aero-propulsive models
- Conventional methods do not efficiently characterize complex eVTOL aircraft
- Previous research has studied and addressed:
  - Static wind-tunnel testing[1,2,3]
  - Free-motion 3DOF wind-tunnel testing[4]
  - Simulated flight-test system identification[5]
- Extension and demonstration in flight testing



Static DOE testing with multisine inputs[2]



Free-motion testing with multisine inputs[4]

1. Simmons, B. M., and Murphy, P. C., "Aero-Propulsive Modeling for Tilt-Wing, Distributed Propulsion Aircraft Using Wind Tunnel Data," *Journal of Aircraft*, Vol. 59, No. 5, 2022, pp. 1162–1178.
2. 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 Forum*, June 2022.
3. Simmons, B. M., and Busan, R. C., "Statistical Wind-Tunnel Experimentation Advancements for eVTOL Aircraft Aero-Propulsive Model Development," *AIAA SciTech Forum*, Jan. 2024.
4. Simmons, B. M., Ackerman, K. A., and Asper, G. D., "Aeropropulsive Damping Characterization for eVTOL Aircraft Using Free Motion Wind-Tunnel Testing," *Journal of Aircraft*, Article in Advance (Oct. 2025).
5. Simmons, B. M., "System Identification Approach for eVTOL Aircraft Demonstrated Using Simulated Flight Data," *Journal of Aircraft*, Vol. 60, No. 4, 2023, pp. 1078–1093.

RAVEN-SWFT

Research **A**ircraft for e**V**TOL **E**nabling Tech**N**ologies (RAVEN)[1]
Subscale **W**ind-Tunnel and **F**light **T**est (SWFT) Vehicle[2]

- Subscale tiltrotor electric vertical takeoff and landing (eVTOL) aircraft configuration
- Wind-tunnel and flight-test research
- Similar scale to NASA LA-8 with expanded utility
- 24 independent control effectors
  - Six proprotor speeds $(n_1, n_2, \ldots, n_6)$
  - Six collective angles $(\delta_{c_1}, \delta_{c_2}, \ldots, \delta_{c_6})$
  - Four nacelle tilt angles $(\delta_{t_1}, \delta_{t_2}, \delta_{t_3}, \delta_{t_4})$
  - Six flaperons $(\delta_{f_1}, \delta_{f_2}, \ldots \delta_{f_6})$
  - Stabilator (δ_s) and Rudder (δ_r)
- 38 lb, 5.7 ft wingspan, 19.5 in diam. proprotors
- 28.6% scale version of a 1000-lb class vehicle
- Built for modeling and controls research





1. https://www.nasa.gov/raven/
2. Geuther, S. C., Simmons, B. M., and Ackerman, K. A., "Overview of the Subscale RAVEN Flight Controls and Modeling Testbed," *VFS Forum 80*, May 2024.

RAVEN-SWFT Development and Testing

- Baseline wind-tunnel testing[1]
  - Isolated proprotor test
  - Static full-airframe test
  - Dynamic 3DOF free-motion test
- Custom unified flight control algorithm[1]
  - Nested-loop architecture
  - Model-based control design approach
  - Scheduling with dynamic pressure
  - Integrated using MathWorks® UAV Toolbox
- Ongoing flight-test envelope expansion
- Low-speed system identification results



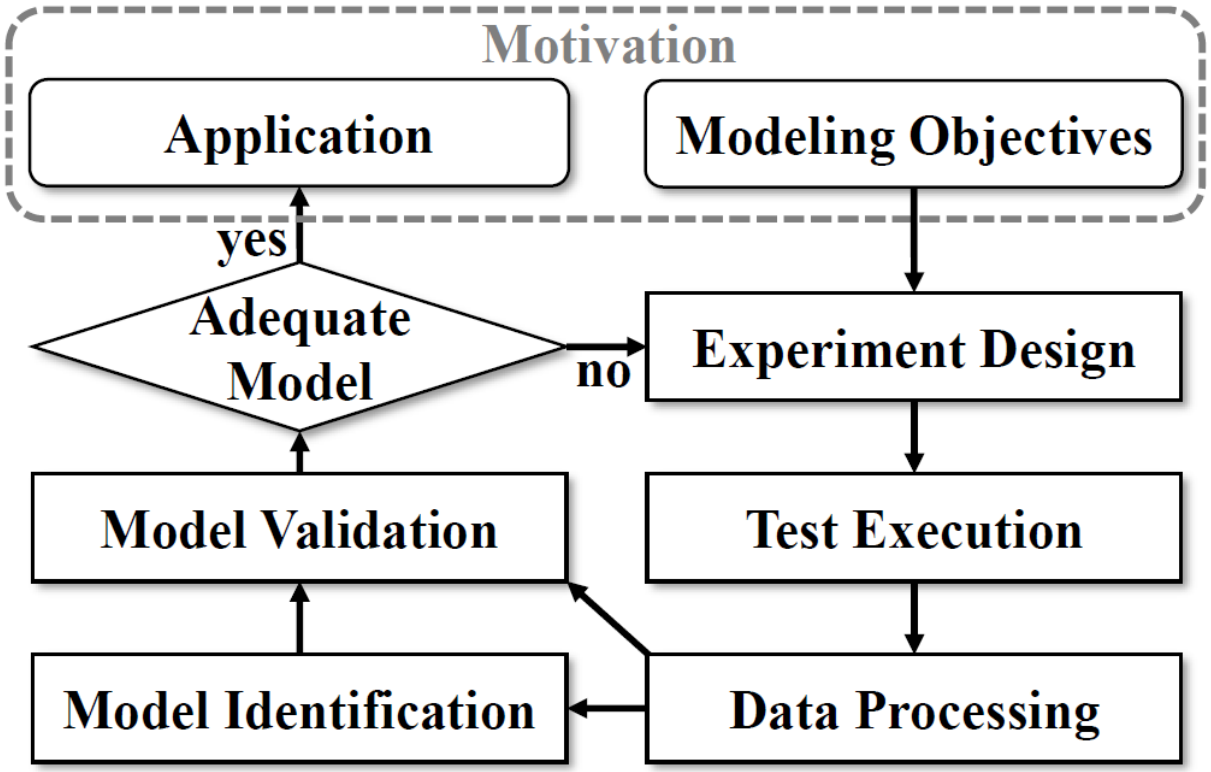


RAVEN-SWFT flight testing.

1. Simmons, B. M., Ackerman, K. A., Asper, G. D., Gray, M. N., Snyder, S. M., Axten, R. M., Geuther, S. C., and Chan, R., "Subscale Tiltrotor eVTOL Aircraft Dynamic Modeling and Flight Control Software Development," *VFS Annual Forum*, May 2025.

System Identification Approach

- Development of a mathematical model from flight-test data
- Present motivation:
  - Demonstration of system ID approach
  - Improve vehicle aero-propulsive model
- Desired attributes:
  - Open-loop model identification
  - Efficient flight-test execution
  - Determine the independent effectiveness of all controls
  - Include nonlinear aerodynamics and control interaction effects
- System IDentification Programs for AirCraft (SIDPAC)[1] software

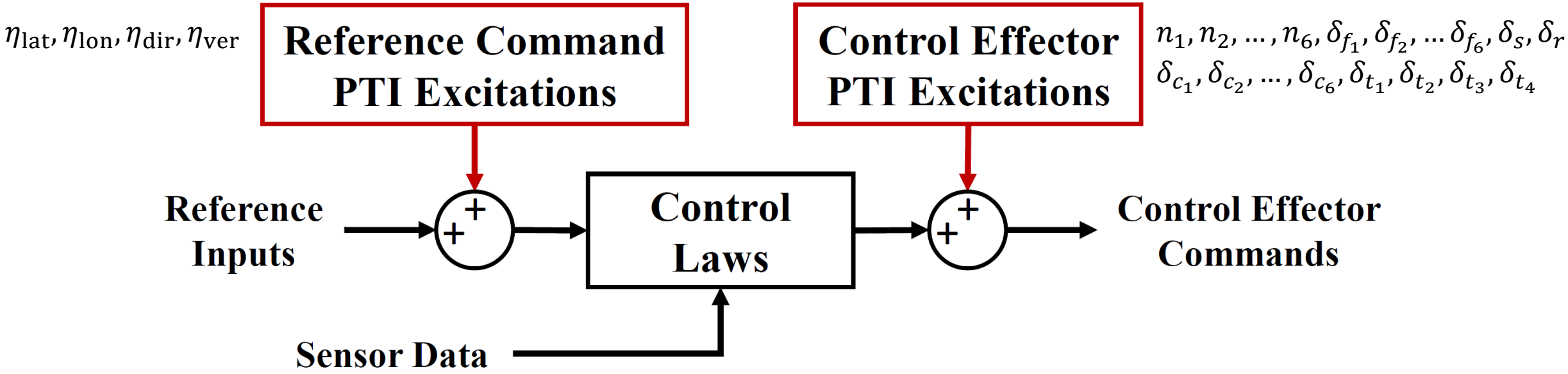


General system identification process.

1. https://software.nasa.gov/software/LAR-16100-1

Experiment Design Overview

- **Objective:** generate informative data for model identification
- Multiple-input excitation required for efficient testing → multisines
- Programmed test inputs (PTIs) integrated into flight control software
- Includes both reference command and control effector PTI excitations



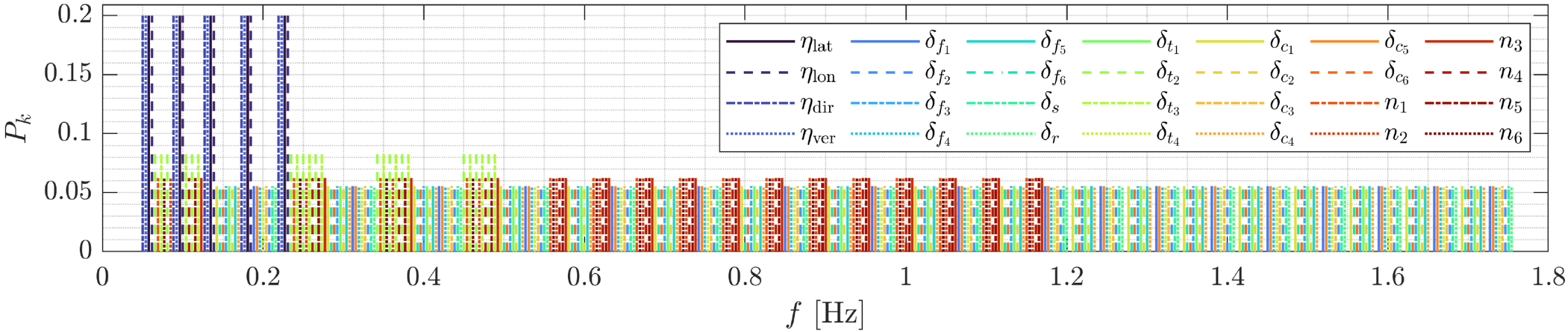
Programmed test input injections relative to the control laws.

Multisine Input Design

- Orthogonal phase-optimized multisine inputs[1,2]
- 28 unique multisine PTI excitation signals
- Simultaneous excitation in all axes
- Input design details are given in the paper

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

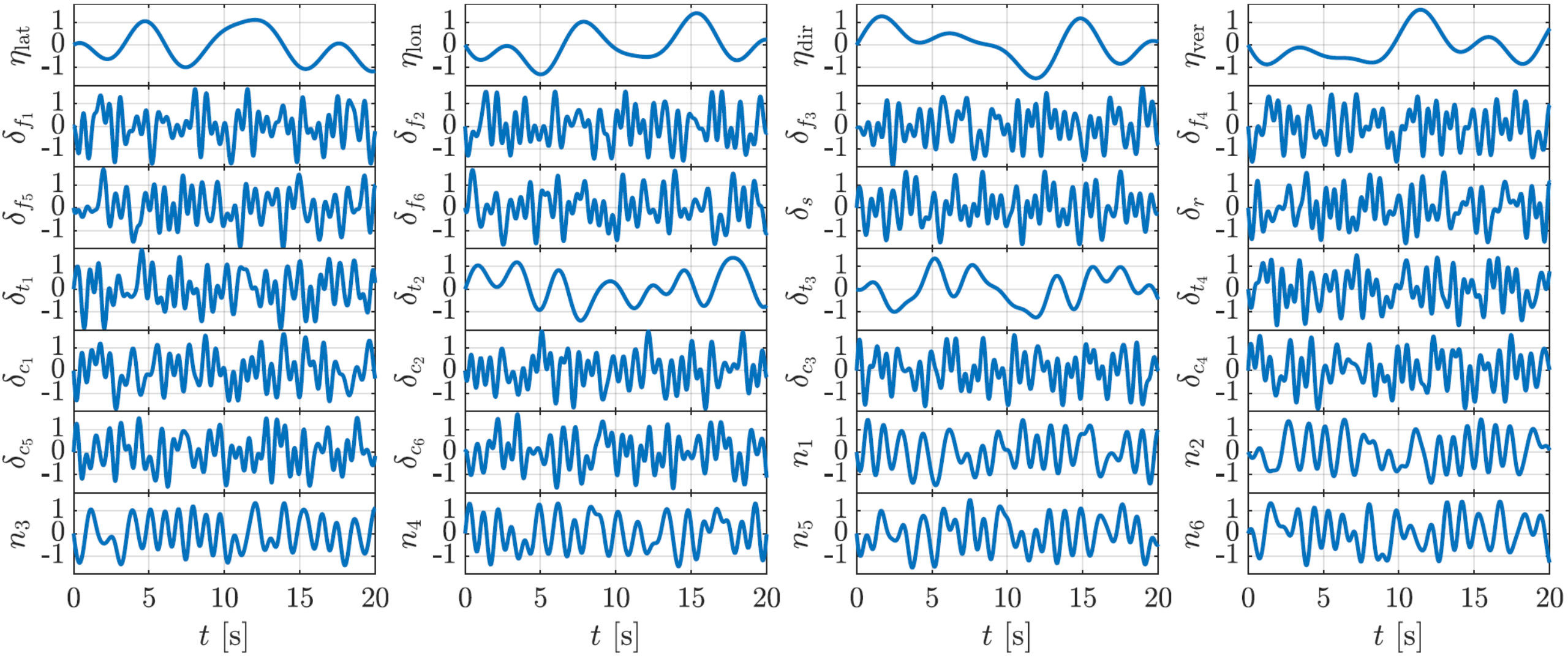
$u_j(t)$ – jth multisine signal
A – signal amplitude
P_k – kth power fraction
T – fundamental period
ϕ_k – kth phase angle



RAVEN-SWFT vehicle multisine input spectra.

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.

RAVEN-SWFT Multisine Signals



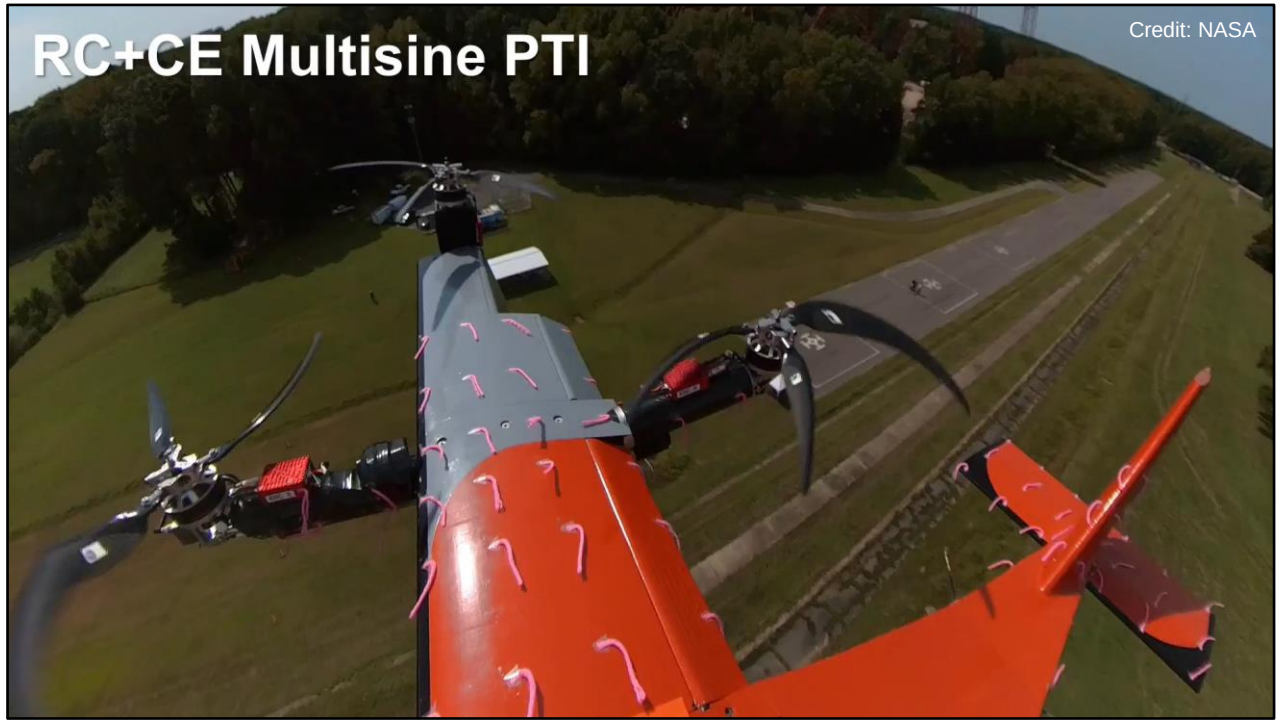
Normalized reference command and control effector multisine inputs.

Hover Flight-Test Maneuvers

- Multiple maneuvers were considered and studied for hover system ID
- Two maneuver types applying multisine inputs were preferred
  - Control effector (CE) multisine maneuver
  - Reference command and control effector (RC+CE) multisine maneuver



Hover CE multisine maneuver.



Hover RC+CE multisine maneuver.

Hover Maneuvers/Observations

CE = Control Effector
RC = Reference Command

CE multisine maneuver

- Larger control excitations
- Smaller u, v, w, r perturbations
- Low correlation
- Improved control derivatives

RC+CE multisine maneuver

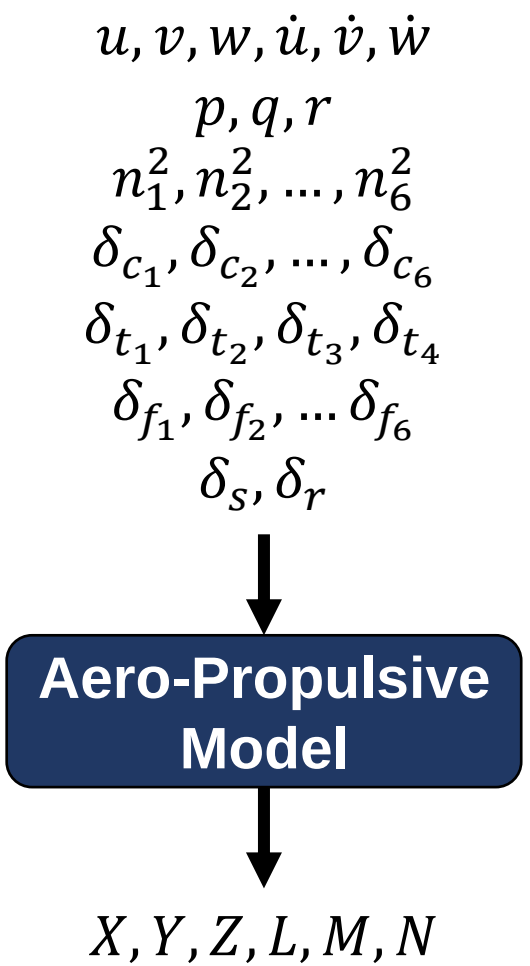
- Larger u, v, w, r perturbations
- Smaller control excitations
- Low correlation
- Improved state derivatives





Model Identification Approach

- Aero-propulsive modeling framework tailored to eVTOL aircraft[1]
- Explanatory variables:
  - Body-axis translational velocity components (u, v, w) and derivatives $(\dot{u}, \dot{v}, \dot{w})$
  - Body-axis angular velocity components (p, q, r)
  - Squared proprotor rotational speeds[2] $(n_1^2, n_2^2, \dots, n_6^2)$ → Linear thrust changes
  - Control deflection angles $(\delta_{c_1}, \delta_{c_2}, \dots, \delta_{c_6}, \delta_{t_1}, \delta_{t_2}, \delta_{t_3}, \delta_{t_4}, \delta_{f_1}, \delta_{f_2}, \dots \delta_{f_6}, \delta_s, \delta_r)$
- Response variables (inferred from other measurements):
  - Dimensional body-axis aero-propulsive forces (X, Y, Z)
  - Dimensional body-axis aero-propulsive moments (L, M, N)
- Flight condition variable: airspeed (V)
- Response surface equations (RSEs) developed at each condition
  - Model structure determination: combination of multivariate orthogonal function modeling (MOF)[3] and stepwise regression (SWR)[3]
  - Parameter estimation: complex least-squares regression[3]
  - Final parameter estimates computed using multiple maneuvers



1. Simmons, B. M., and Murphy, P. C., "Aero-Propulsive Modeling for Tilt-Wing, Distributed Propulsion Aircraft Using Wind Tunnel Data," *Journal of Aircraft*, Vol. 59, No. 5, 2022, pp. 1162–1178.
2. Simmons, B. M., Rapsomanikis, A., Jacobellis, G., Ofodile, N., Hamilton, T., and Ma, M., "Flight-Test System Identification Methodology and Hover Results for a Vectored-Thrust eVTOL Aircraft," *VFS Annual Forum*, May 2025.
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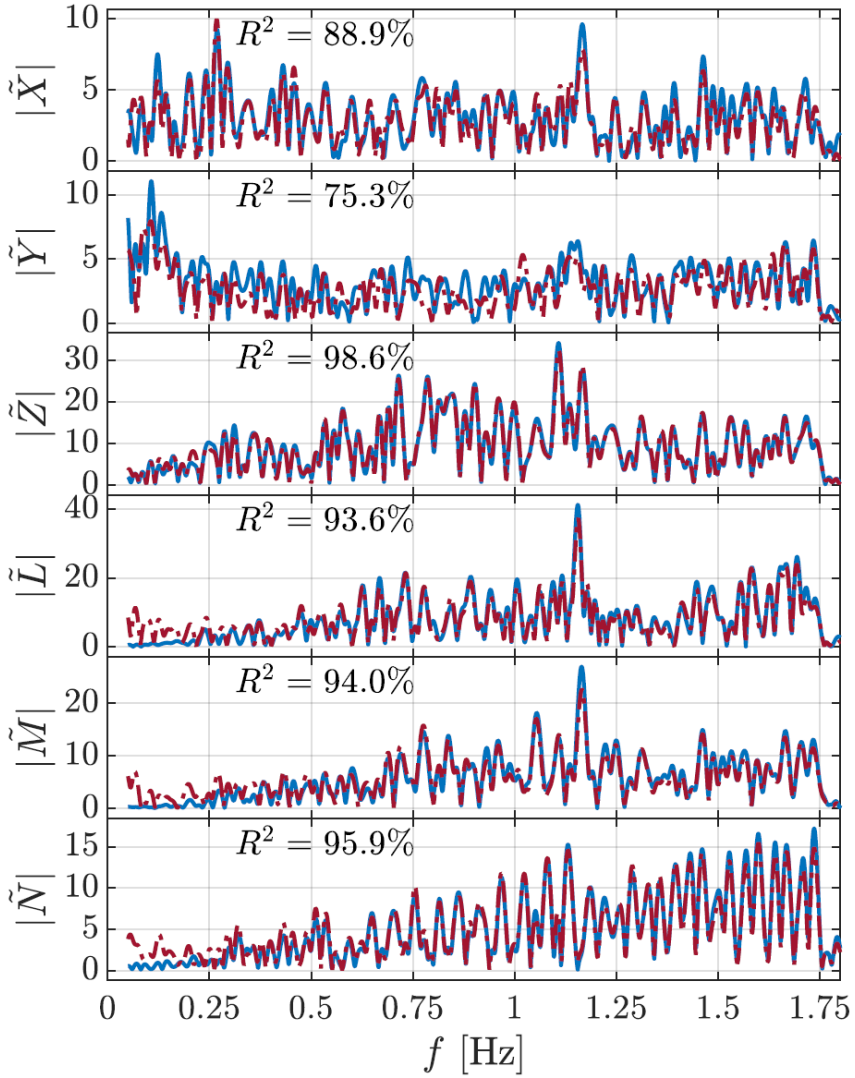
Hover Model Structure

- Nonlinear terms considered/included
- Model parameter symmetrization

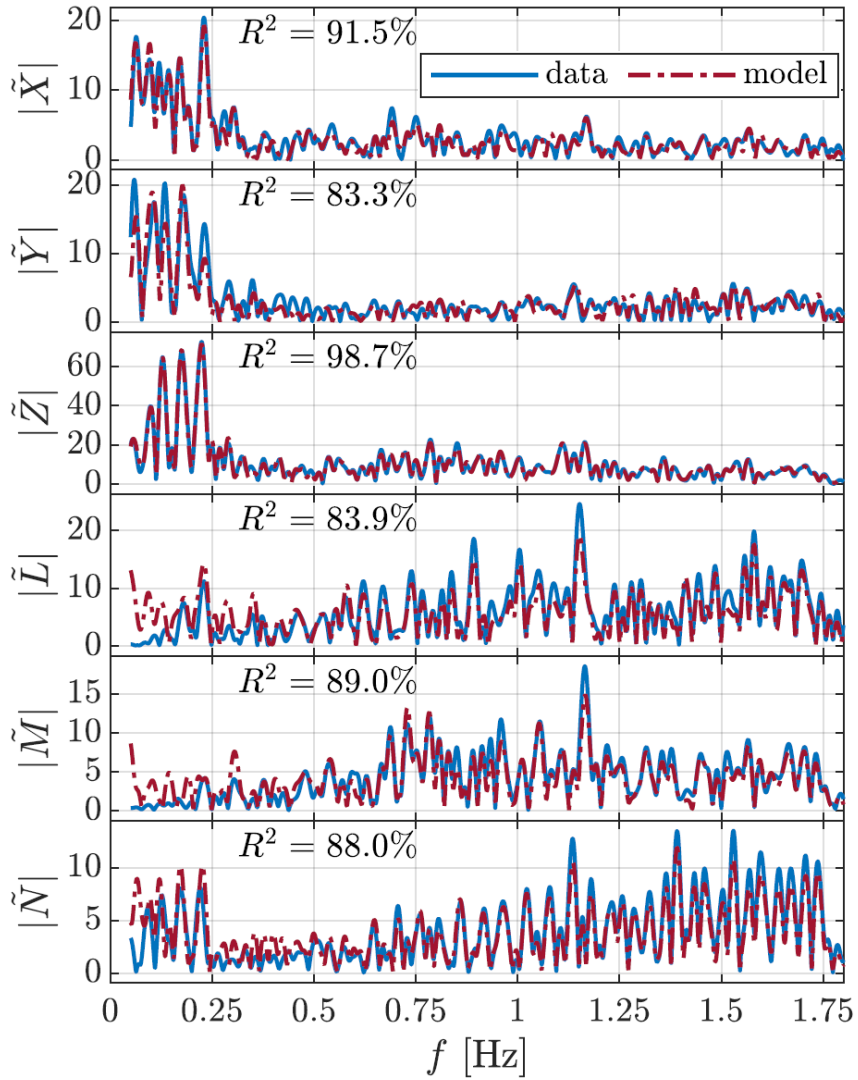
$$
\begin{aligned}
X &= X_u u + X_w w + X_{wq} wq + X_{\delta_{f16}}(\delta_{f_1} + \delta_{f_6}) + X_{\delta_{t14}}(\delta_{t_1} + \delta_{t_4}) + X_{\delta_{t23}}(\delta_{t_2} + \delta_{t_3}) + X_{\delta_{c23}}(\delta_{c_2} + \delta_{c_3}) \\
&\quad + X_{\delta_{c56}}(\delta_{c_5} + \delta_{c_6}) + X_{n_{23}^2}(n_2^2 + n_3^2) + X_{n_{56}^2}(n_5^2 + n_6^2) + X_{n_{14}^2\delta_{t14}}(n_1^2\delta_{t_1} + n_4^2\delta_{t_4}) + X_{n_{23}^2\delta_{t23}}(n_2^2\delta_{t_2} + n_3^2\delta_{t_3}) \\
&\quad + X_{\delta_{c14}\delta_{t14}}(\delta_{c_1}\delta_{t_1} + \delta_{c_4}\delta_{t_4}) + X_{\delta_{c23}\delta_{t23}}(\delta_{c_2}\delta_{t_2} + \delta_{c_3}\delta_{t_3}) + X_o \\
Y &= Y_v v + Y_{\delta_{t14}}(\delta_{t_1} - \delta_{t_4}) + Y_{\delta_{t23}}(\delta_{t_2} - \delta_{t_3}) + Y_{\delta_{c14}}(\delta_{c_1} - \delta_{c_4}) + Y_{\delta_{c23}}(\delta_{c_2} - \delta_{c_3}) + Y_{\delta_{c56}}(\delta_{c_5} - \delta_{c_6}) \\
&\quad + Y_{n_{14}^2}(n_1^2 - n_4^2) + Y_{n_{23}^2}(n_2^2 - n_3^2) + Y_{n_{56}^2}(n_5^2 - n_6^2) \\
Z &= Z_w w + Z_{uq} uq + Z_{vp} vp + Z_{\dot{w}} \dot{w} + Z_{\delta_{c14}}(\delta_{c_1} + \delta_{c_4}) + Z_{\delta_{c23}}(\delta_{c_2} + \delta_{c_3}) + Z_{\delta_{c56}}(\delta_{c_5} + \delta_{c_6}) + Z_{n_{14}^2}(n_1^2 + n_4^2) \\
&\quad + Z_{n_{23}^2}(n_2^2 + n_3^2) + Z_{n_{56}^2}(n_5^2 + n_6^2) + Z_o \\
L &= L_v v + L_p p + L_{wr} wr + L_{vr} vr + L_{\delta_{f16}}(\delta_{f_1} - \delta_{f_6}) + L_{\delta_{t14}}(\delta_{t_1} - \delta_{t_4}) + L_{\delta_{c14}}(\delta_{c_1} - \delta_{c_4}) + L_{\delta_{c23}}(\delta_{c_2} - \delta_{c_3}) \\
&\quad + L_{\delta_{c56}}(\delta_{c_5} - \delta_{c_6}) + L_{n_{14}^2}(n_1^2 - n_4^2) + L_{n_{23}^2}(n_2^2 - n_3^2) + L_{n_{56}^2}(n_5^2 - n_6^2) \\
M &= M_u u + M_w w + M_{uq} uq + M_{wq} wq + M_{vp} vp + M_{\dot{w}} \dot{w} + M_{\delta_{c23}}(\delta_{c_2} + \delta_{c_3}) + M_{\delta_{c56}}(\delta_{c_5} + \delta_{c_6}) \\
&\quad + M_{n_{23}^2}(n_2^2 + n_3^2) + M_{n_{56}^2}(n_5^2 + n_6^2) + M_o \\
N &= N_r r + N_{\delta_{f16}}(\delta_{f_1} - \delta_{f_6}) + N_{\delta_{t14}}(\delta_{t_1} - \delta_{t_4}) + N_{\delta_{t23}}(\delta_{t_2} - \delta_{t_3}) + N_{\delta_{c14}}(\delta_{c_1} - \delta_{c_4}) + N_{\delta_{c23}}(\delta_{c_2} - \delta_{c_3}) \\
&\quad + N_{n_{14}^2}(n_1^2 - n_4^2) + N_{n_{23}^2}(n_2^2 - n_3^2) + N_{n_{14}^2\delta_{t14}}(n_1^2\delta_{t_1} - n_4^2\delta_{t_4}) + N_{\delta_{c14}\delta_{t14}}(\delta_{c_1}\delta_{t_1} - \delta_{c_4}\delta_{t_4}) + I_p(\textstyle\sum_{i=1}^{6}(-1)^i\dot{\Omega}_i)
\end{aligned}
$$

Frequency-Domain Hover Modeling Results

- Complex least-squares regression
- Maneuvers first analyzed separately
- Good overall fits
- Differences for each maneuver type
- Similar results for repeated maneuvers



CE multisine maneuver

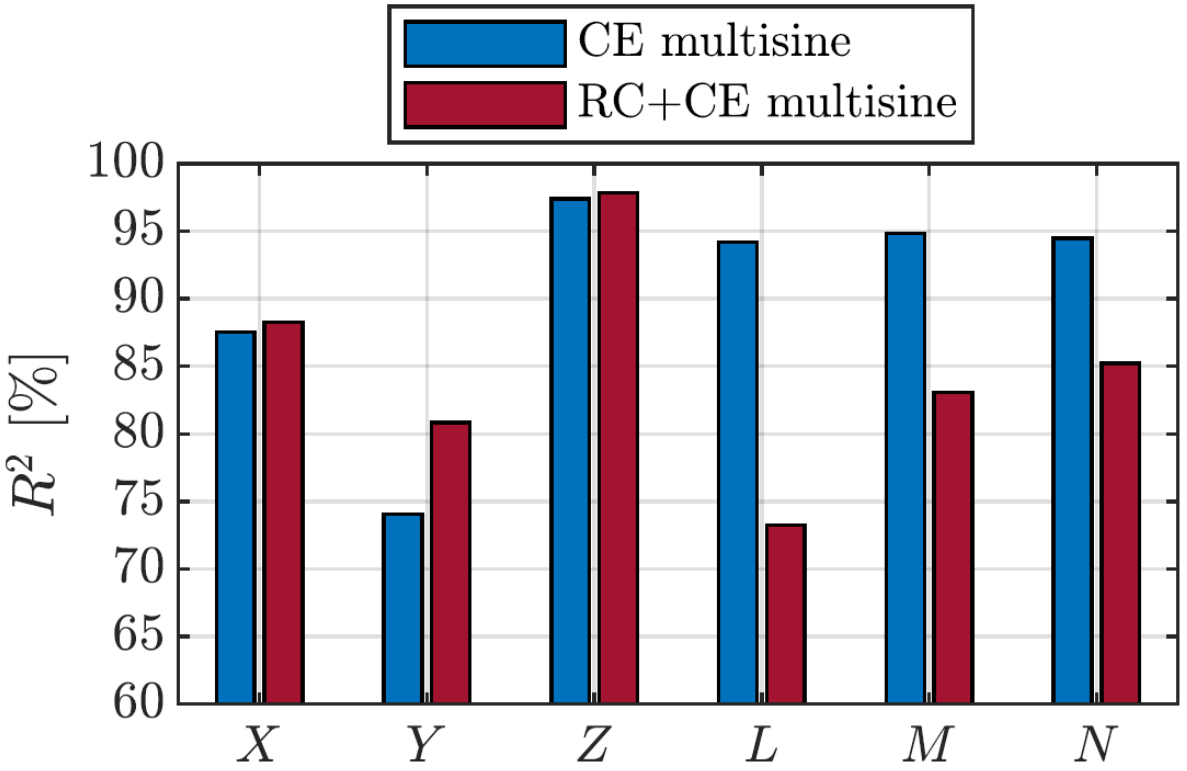


RC+CE multisine maneuver

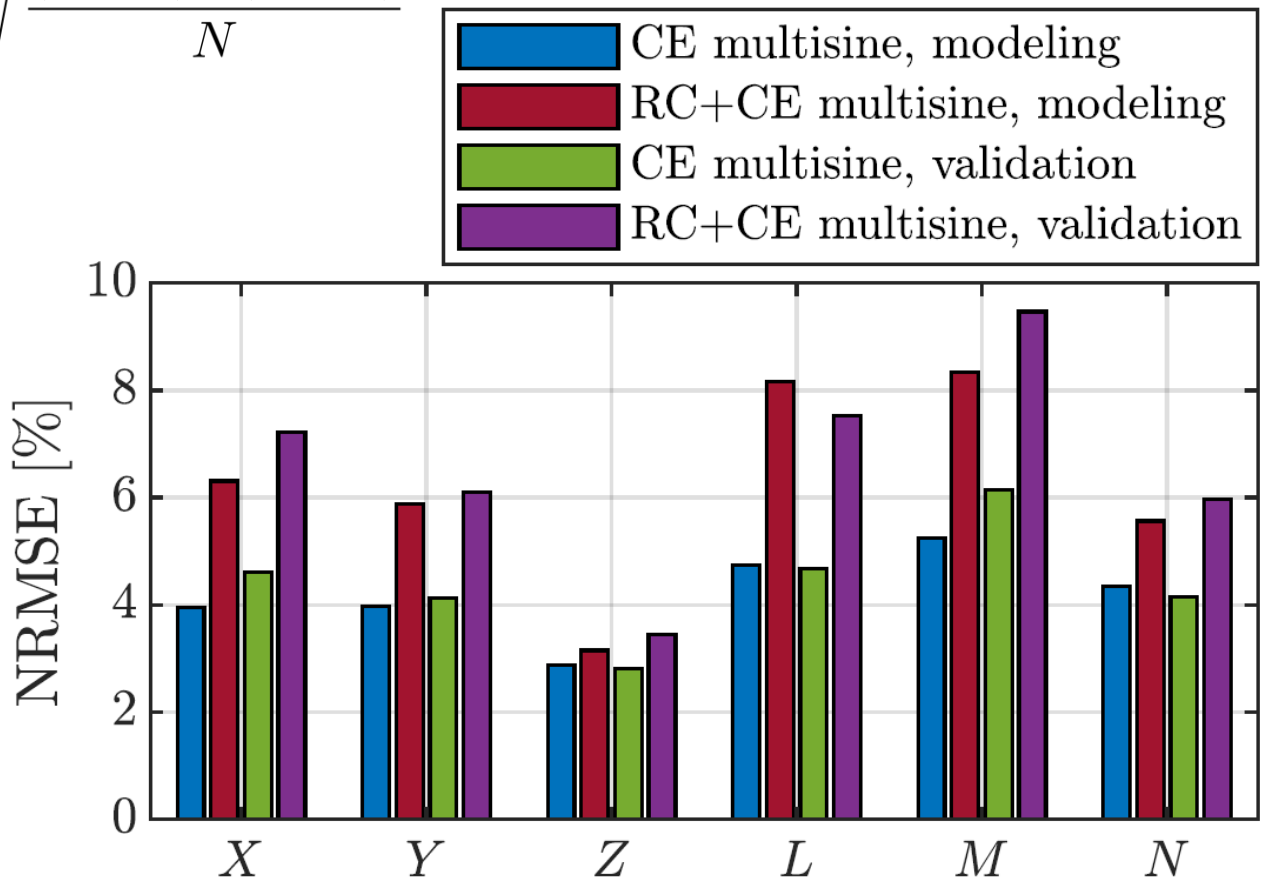
Comparison of response data and model fit for example maneuvers.

Hover Modeling Results Summary

$$\text{NRMSE} = 100 \times \frac{1}{\text{range}(\boldsymbol{z}_m)} \sqrt{\frac{(\boldsymbol{z}-\hat{\boldsymbol{y}})^T (\boldsymbol{z}-\hat{\boldsymbol{y}})}{N}}$$



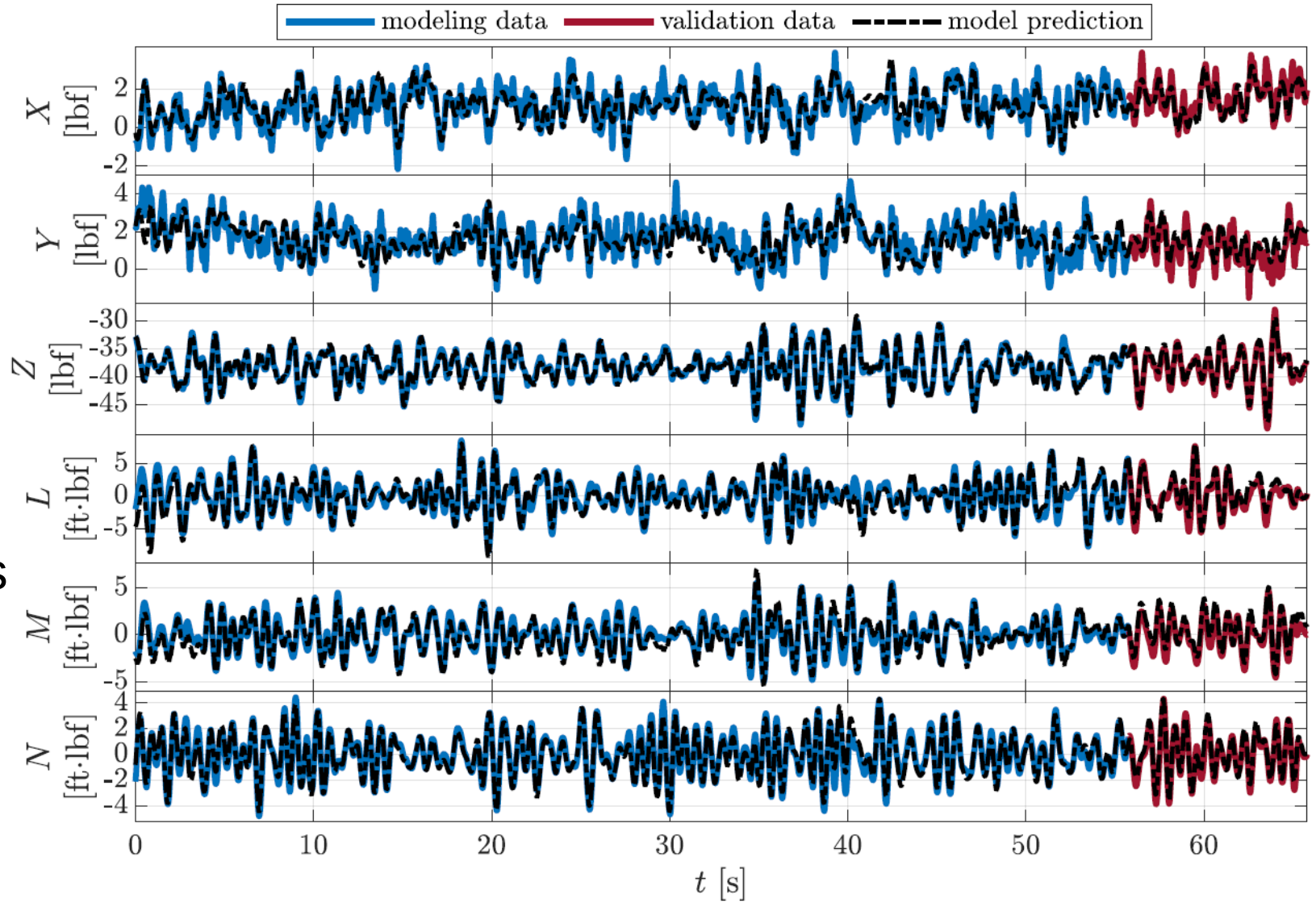
Average frequency-domain model identification R^2 for each maneuver type.



Modeling and validation NRMSE in the time-domain for each maneuver type.

Hover Model Prediction: CE Multisine

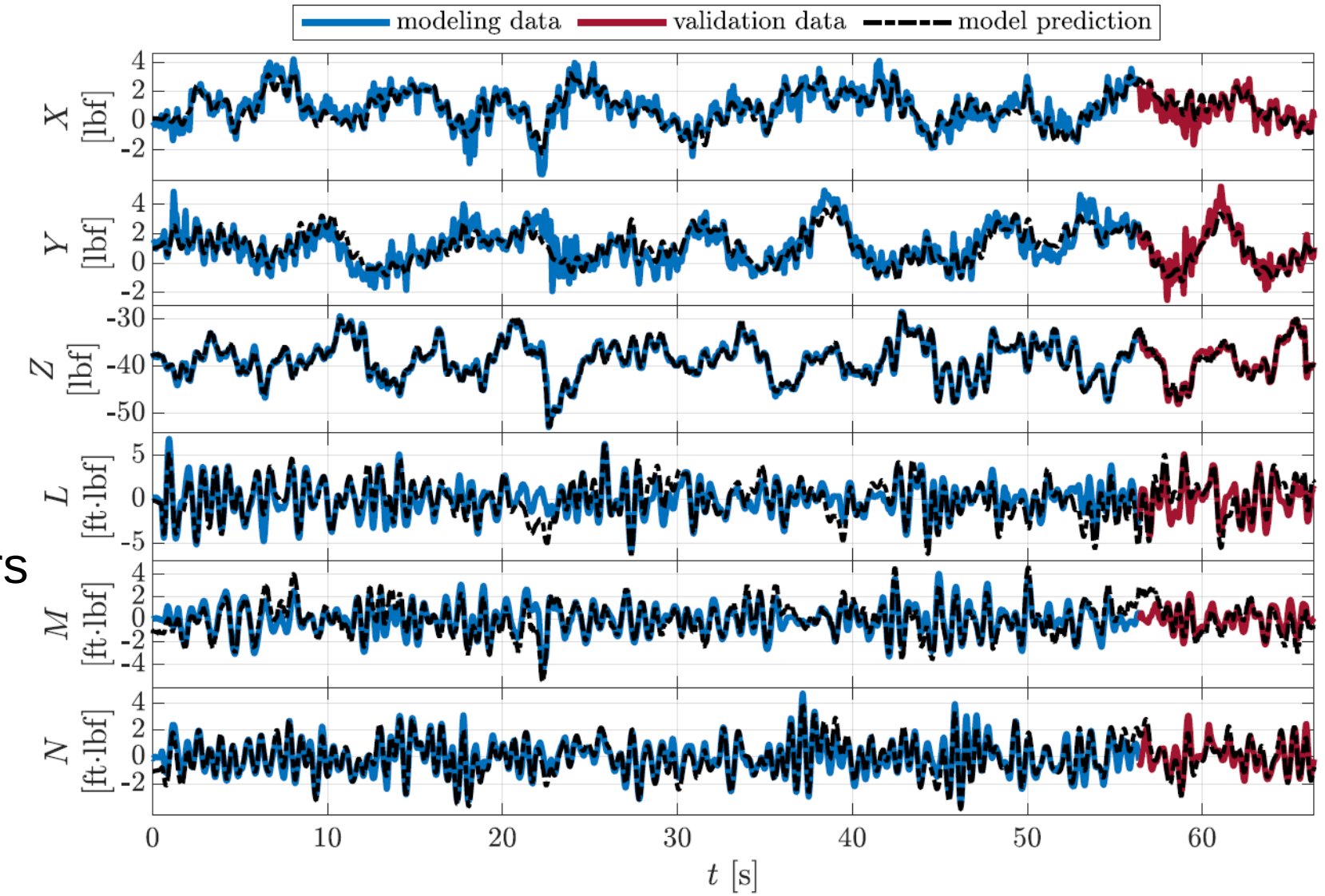
- Time-domain comparison of model prediction to smoothed response data
- Last 10 seconds of each maneuver withheld for model validation
- Good prediction capability using combined parameters



Comparison of response data and model prediction.

Hover Model Prediction: RC+CE Multisine

- Time-domain comparison of model prediction to smoothed response data
- Last 10 seconds of each maneuver withheld for model validation
- Good prediction capability using combined parameters



Comparison of response data and model prediction.

Concluding Remarks

- eVTOL aircraft present new aero-propulsive modeling challenges
- Efficient experiment design using orthogonal phase-optimized multisine inputs
  - Two multisine maneuver types were employed and found to have unique utility
  - Programmed test input injections both before and after the control laws are important
- Accurate hover models identified with short flight-test maneuver times
- Techniques can be applied throughout transition and for many other vehicles





Questions/Discussion – Thank you for attending.

Acknowledgments

- **Funding:** NASA Transformational Tools and Technologies (TTT) and Flight Demonstrations and Capabilities (FDC) projects
- **Vehicle development and flight testing:** Matthew Gray, Gregory Howland, Ryan Chan, David North, Steven Geuther, Justin Lisee, and Gary Banziger
- **RAVEN-SWFT pilots:** Jody Miller and Brayden Chamberlain
- **Flight controls support:** Garrett Asper, Rachel Axten, and Steven Snyder
- **Project support:** Jacob Schaefer, Siena Whiteside, Jason Welstead, and Michael Acheson



Related eVTOL Aircraft Modeling References

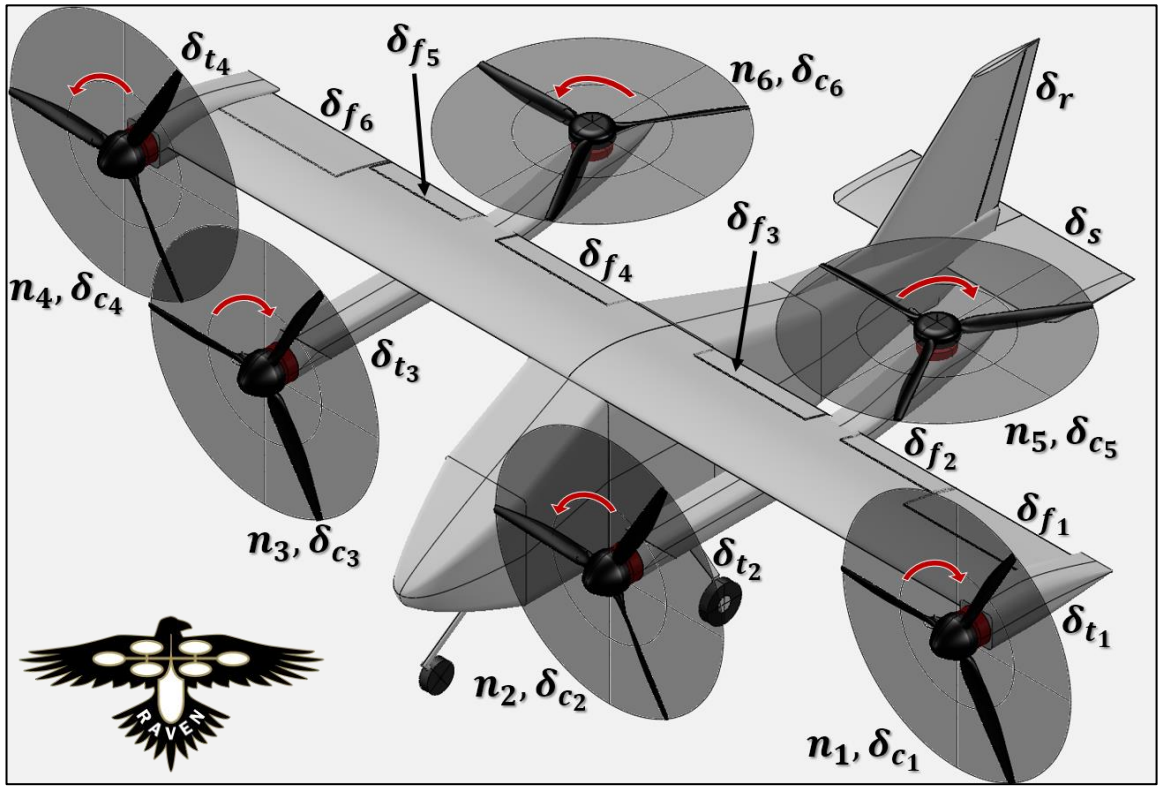
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Advanced Air Mobility (AAM)



NASA RAVEN eVTOL Vehicle

- RAVEN – **R**esearch **A**ircraft for e**V**TOL **E**nabling Tech**N**ologies[1,2]
- Tiltrotor electric vertical takeoff and landing (eVTOL) aircraft configuration
- Vehicles at different scales
- 24 independent control effectors
  - Six proprotor speeds $(n_1, n_2, \ldots, n_6)$
  - Six collective angles $(\delta_{c_1}, \delta_{c_2}, \ldots, \delta_{c_6})$
  - Four nacelle tilt angles $(\delta_{t_1}, \delta_{t_2}, \delta_{t_3}, \delta_{t_4})$
  - Six flaperons $(\delta_{f_1}, \delta_{f_2}, \ldots \delta_{f_6})$
  - Stabilator (δ_s) and rudder (δ_r)
- Created to address eVTOL challenges
- Research platform providing open geometry, data, and methods



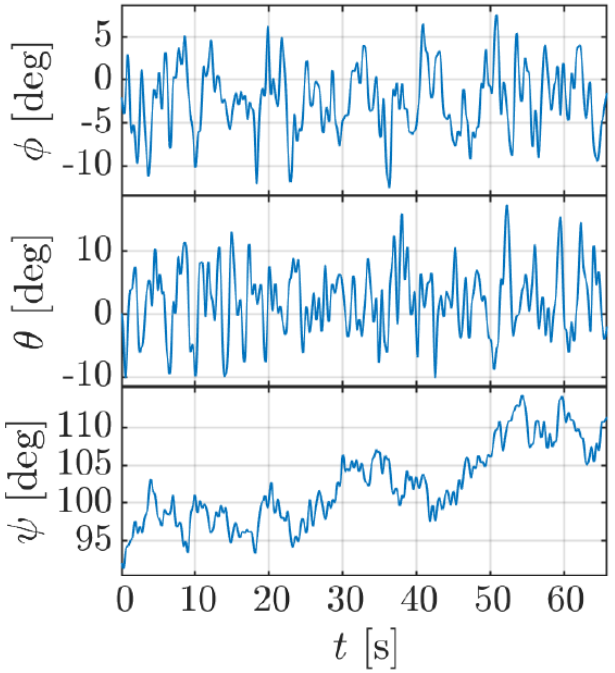
RAVEN control effector definitions.

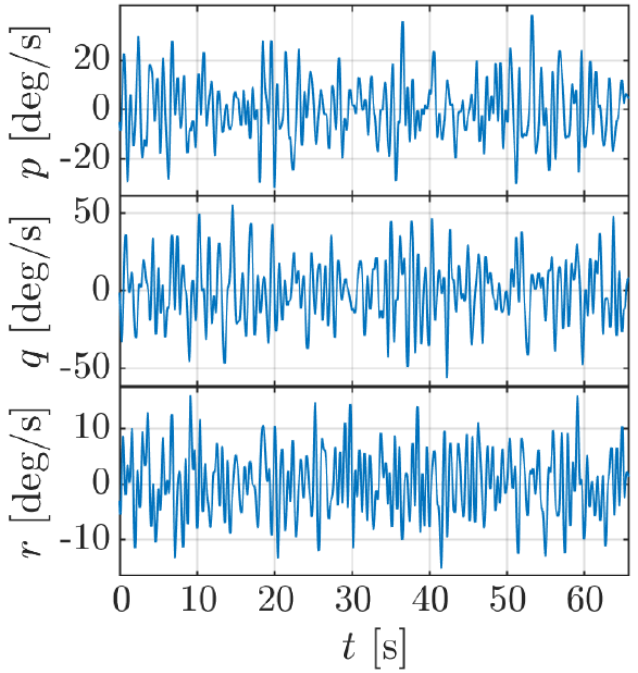
1. https://www.nasa.gov/raven/
2. German, B. J., Jha, A., Whiteside, S. K. S., and Welstead, J. R., "Overview of the Research Aircraft for eVTOL Enabling techNologies (RAVEN) Activity," *AIAA AVIATION Forum*, June 2023.

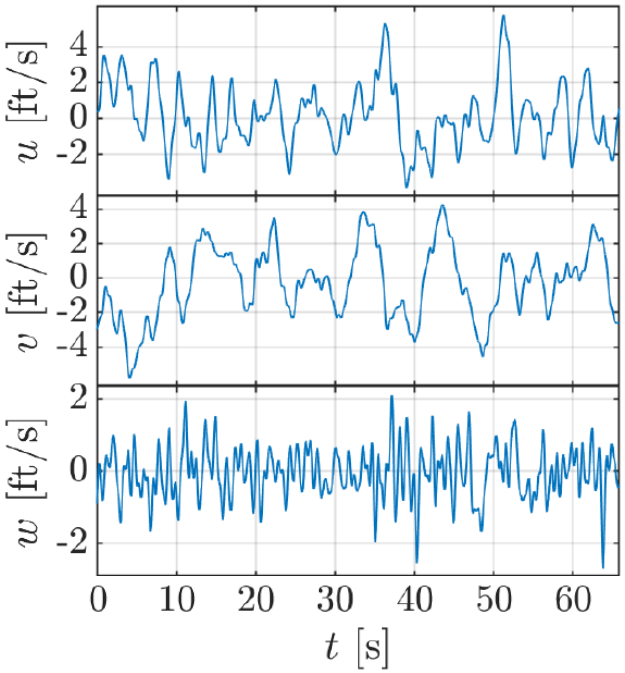
Hover Flight Data

CE multisine

- Larger control excitations
- Smaller u, v, w, r perturbations
- Low correlation







RC+CE multisine

- Smaller control excitations
- Larger u, v, w, r perturbations
- Low correlation

