



Flight-Test System Identification for eVTOL Aircraft

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Vehicle Dynamics and Control Branch

NASA Langley Research Center

E-VTOL Flight Test Council Meeting

03 March 2026

Contents



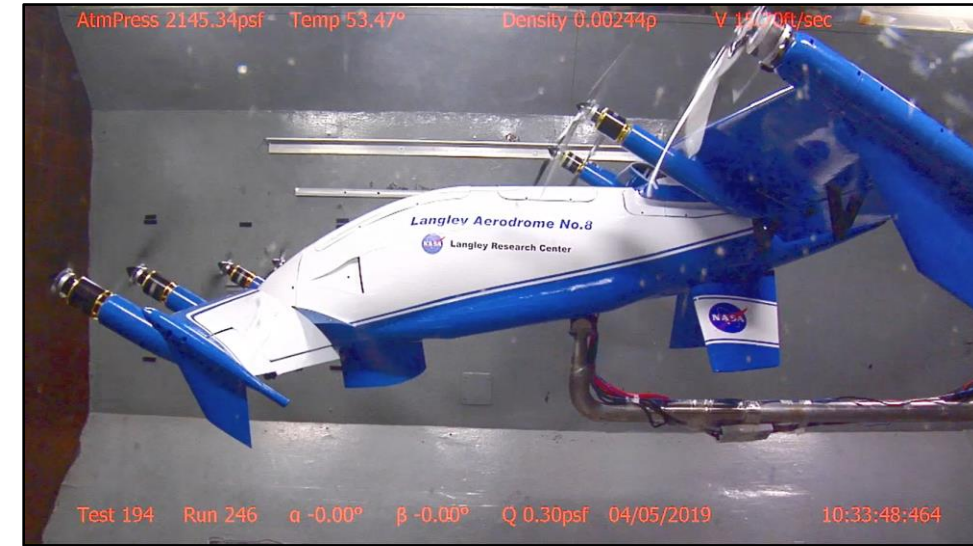
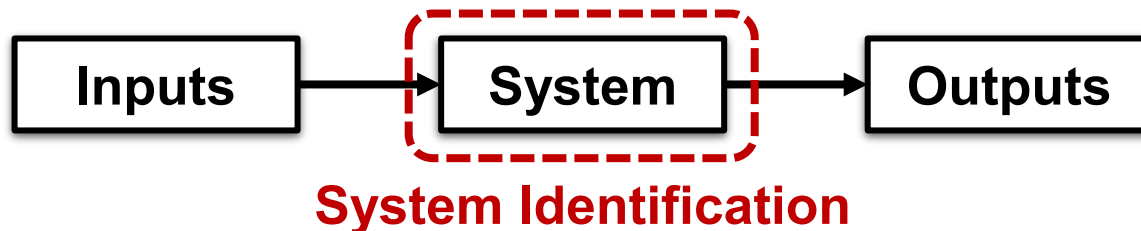
- Overview and motivation
- Background research
- Two eVTOL flight-test applications
 - System identification approach
 - Flight-test experiment design
 - Aero-propulsive modeling results
- Concluding remarks
- Questions/discussion



Research Overview



- **Topic:** Electric vertical takeoff and landing (eVTOL) aircraft system identification
- Development of nonlinear aircraft mathematical models
- Flight dynamics simulations
- Models identified using data from:
 - Computational predictions
 - Wind-tunnel testing
 - Flight testing



NASA LA-8 wind-tunnel testing.



NASA LA-8 flight testing.

Research Motivation

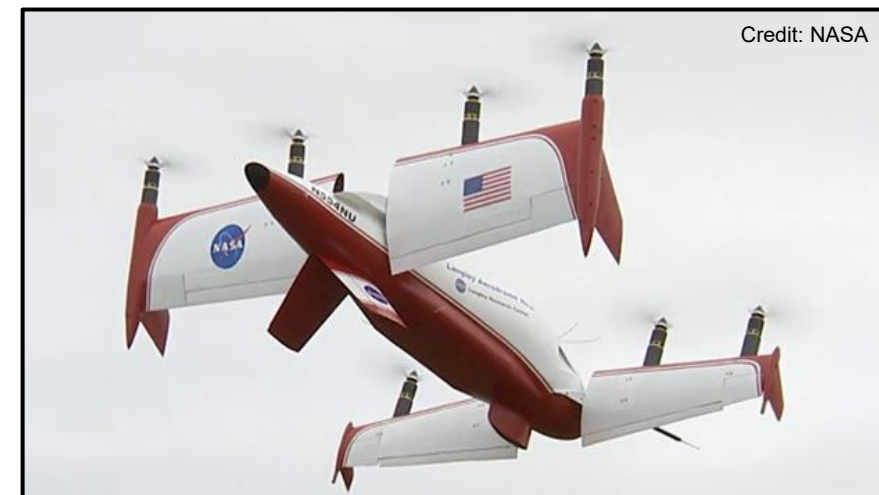


- Recent technology advancements enabling practical eVTOL aircraft
- Multidisciplinary need for flight simulations driven by high-fidelity aero-propulsive models
- eVTOL vehicles are a new class of aircraft with numerous challenges
- Conventional methods do not efficiently characterize complex eVTOL aircraft
- New eVTOL aircraft flight testing and modeling strategies are required

Objective: Advance flight testing and modeling strategies for eVTOL aircraft to efficiently deliver high-fidelity aero-propulsive models



NASA RAVEN-SWFT aircraft



NASA LA-8 aircraft

Advanced Air Mobility (AAM)



Credit: NASA



Background: eVTOL Aircraft Aero-Propulsive Modeling



- LA-8 tiltwing eVTOL aircraft
- Static wind-tunnel testing
- Application of statistically-designed experiments
 - Design of experiments (DOE)
 - Response surface methods (RSM)
- General full-envelope empirical aero-propulsive modeling strategy
- Modeling variables postulated and justified based on vehicle attributes

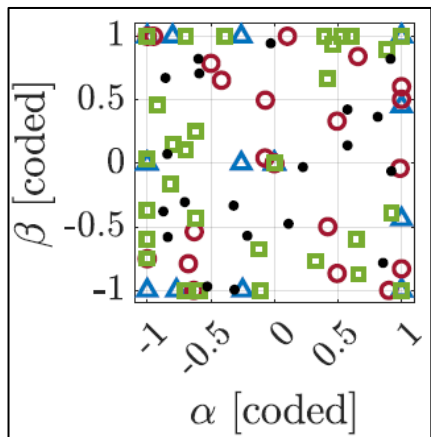


LA-8 DOE/RSM wind-tunnel testing.

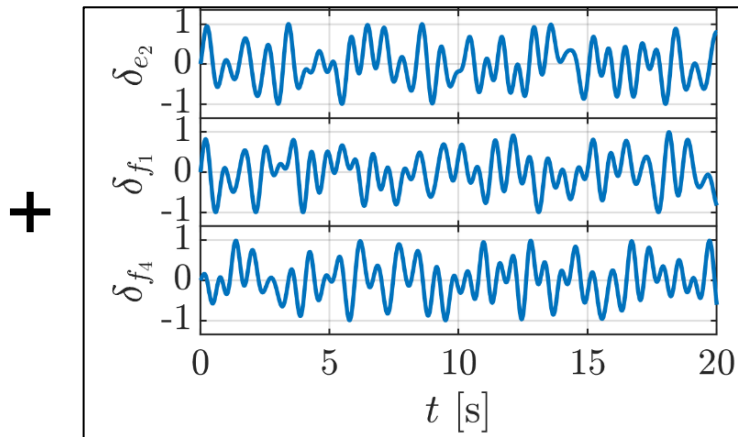
Simmons, B. M., and Murphy, P. C., "Aero-Propulsive Modeling for Tilt-Wing, Distributed Propulsion Aircraft Using Wind Tunnel Data," *Journal of Aircraft*, Vol. 59, No. 5, 2022, pp. 1162–1178. <https://doi.org/10.2514/1.C036351>.

Background: Wind Tunnel Testing with Multisine Inputs

- Hybrid experiment design and wind-tunnel testing strategy
 - Static DOE/RSM testing
 - Orthogonal phase-optimized multisine programmed test input (PTI) excitations
- Factor of five reduction in test time



2D slice of the DOE/RSM design.



Sample multisine PTI signals.



Hybrid DOE/RSM+PTI testing.

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*, June 2022. <https://doi.org/10.2514/6.2022-3603>.

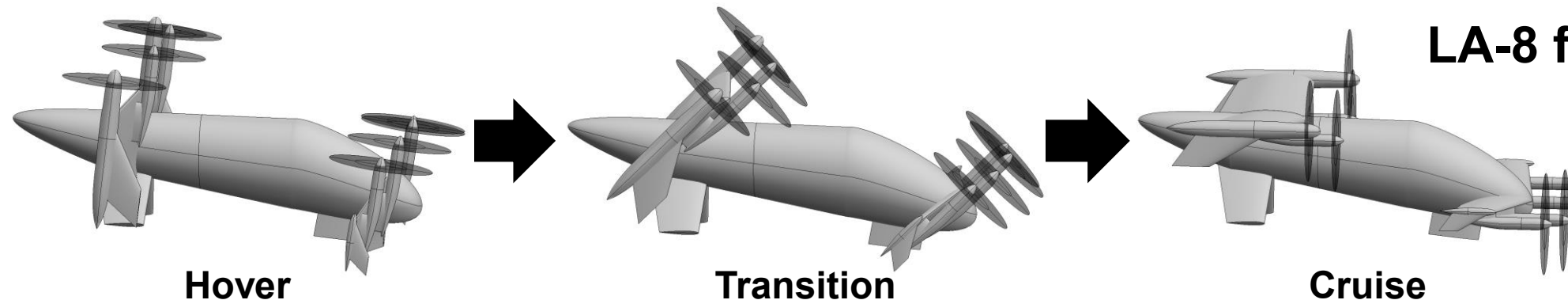
Background: Flight-Test System Identification Approach



- Developed and executed in a high-fidelity LA-8 flight dynamics simulation
- Simultaneous excitation of all controls
- Efficient, accurate, full-envelope model ID
- Overcomes eVTOL aircraft challenges



LA-8 flight test.



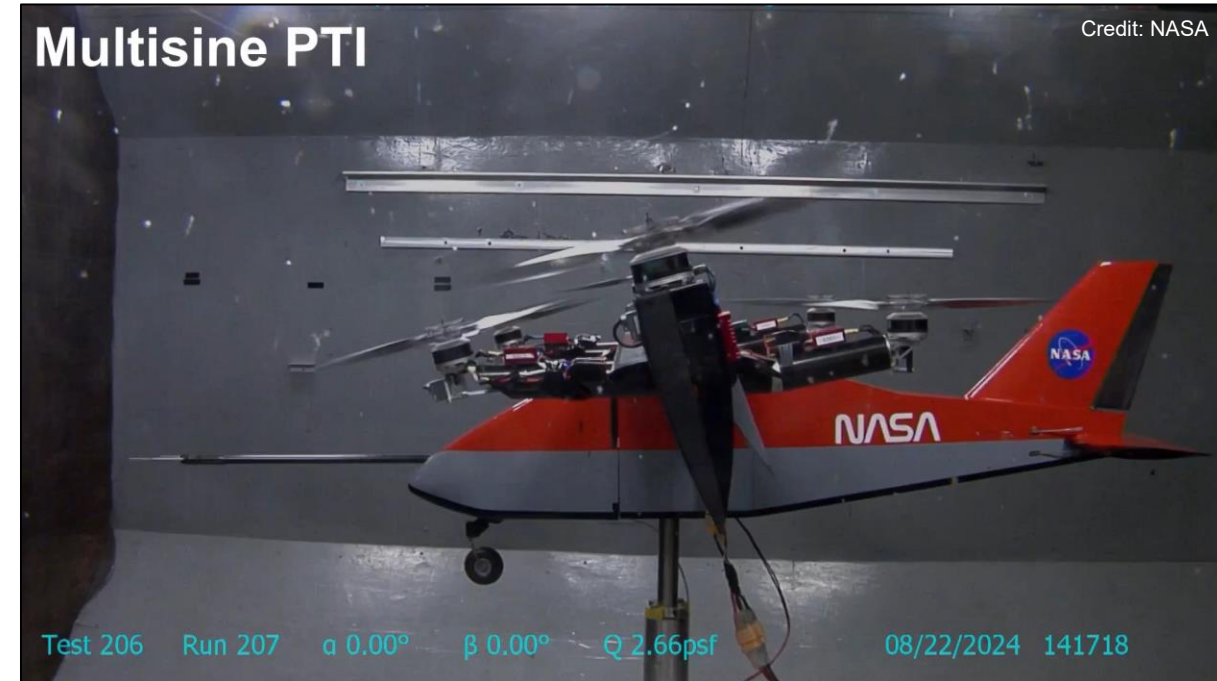
*Complements safe
envelope expansion
flight testing*

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. <https://doi.org/10.2514/1.C036896>.

Background: 3DOF Free-Motion Wind-Tunnel Testing



- RAVEN-SWFT tiltrotor eVTOL aircraft
- Three degree-of-freedom (3DOF) wind-tunnel testing
- Multisine inputs applied to:
 - 24 control effectors
 - Attitude reference commands
- Efficient aero-propulsive modeling
- Validation throughout transition



3DOF testing with multisine inputs.

Simmons, B. M., Ackerman, K. A., and Asper, G. D., “Aero-Propulsive Damping Characterization for eVTOL Aircraft Using Free Motion Wind-Tunnel Testing,” *Journal of Aircraft*, Published Oct. 2025. <https://doi.org/10.2514/1.C038339>.

Flight-Test System ID Applications



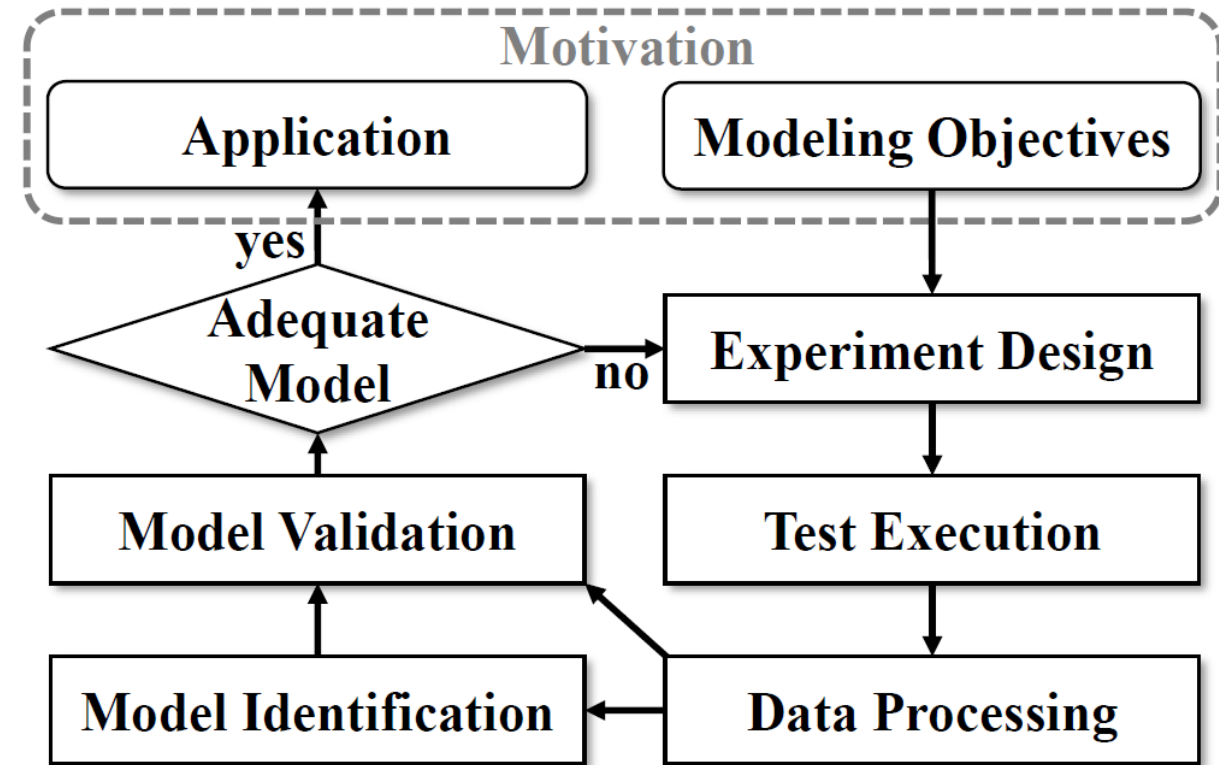
1. Simmons, B. M., Rapsomanikis, A., Jacobellis, G., Ofodile, N., Hamilton, T., and Ma, M., “Flight-Test System Identification Methodology and Hover Results for a Vectored-Thrust eVTOL Aircraft,” *VFS 81st Annual Forum*, May 2025. <https://doi.org/10.4050/F-0081-2025-220>.
2. Simmons, B. M., and Ackerman, K. A., “System Identification for a Subscale Tiltrotor eVTOL Aircraft from Hover Flight-Test Data,” *AIAA SciTech 2026 Forum*, Jan. 2026, <https://doi.org/10.2514/6.2026-2088>.

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System Identification Approach



- Development of a mathematical model from flight-test data
- Present motivation:
 - Demonstration of system ID approach
 - Computational tool validation
 - Improve vehicle aero-propulsive model
 - Simulation for control law design
- Desired attributes:
 - Open-loop model identification
 - Efficient flight-test execution
 - Determine the independent effectiveness of all control effectors
 - Include nonlinear aerodynamics and control interaction effects, if needed
- System Identification Programs for Aircraft (SIDPAC)¹ software



General system identification process.

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



Flight-Test System Identification Methodology and Hover Results for a Vectored-Thrust eVTOL Aircraft

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NASA Langley Research Center

Andrew Rapsomanikis, George Jacobellis, NK Ofodile, Thomas Hamilton, and Max Ma

AIBOT

The Vertical Flight Society's 81st Annual Forum & Technology Display

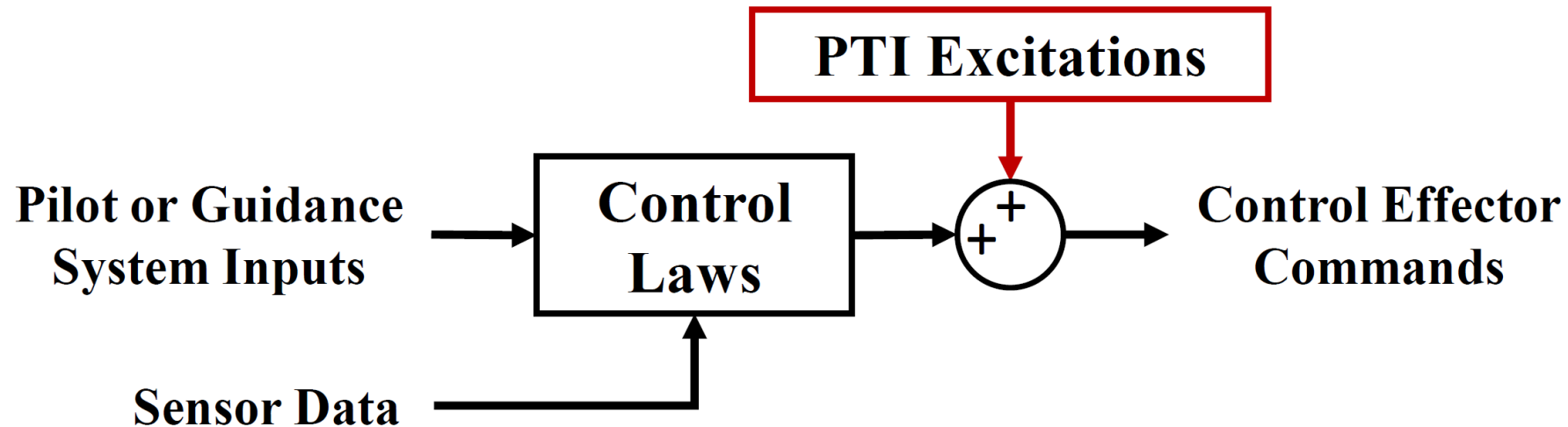
20–22 May 2025

Aircraft: AIBOT 500

- AIBOT prototype 500-lb aircraft
- Transitioning, vectored-thrust, eVTOL configuration
- 8 proprotors ($\Omega_1, \Omega_2, \dots, \Omega_8$)
- 8 control surfaces ($\delta_1, \delta_2, \dots, \delta_8$)
- Proprotor-control surface interactions in all phases of flight
- AIBOT 500 configuration is **not** currently in the public domain
- See www.aibot.ai for updates
- Mass properties
 - Mass/CG determined empirically
 - Moments of inertia estimated from a component build-up approach
- Instrumentation
 - Inertial measurement unit (IMU)
 - Inertial navigation system (INS)
 - Electronic speed controller (ESC) feedback
 - Control surface commands
- Baseline aerodynamics
 - Thrust-stand testing
 - FLIGHTLAB[®] predictions

Experiment Design Overview

- **Objective:** generate informative data for model identification
- Multiple-input excitation required for efficient testing → multisines
- Multisine PTI injection capability integrated into the flight computer



PTI injections relative to the control laws.

Input Design

- Orthogonal phase-optimized multisine inputs^{1,2}
- 16 unique multisine PTI excitation signals
- All aircraft dynamics are simultaneously excited

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

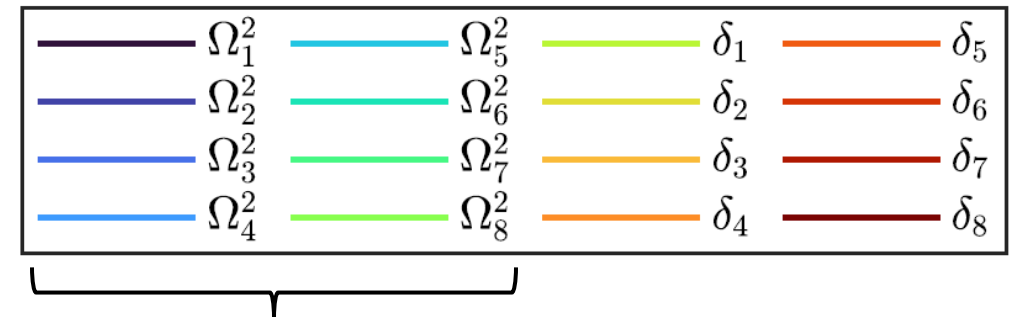
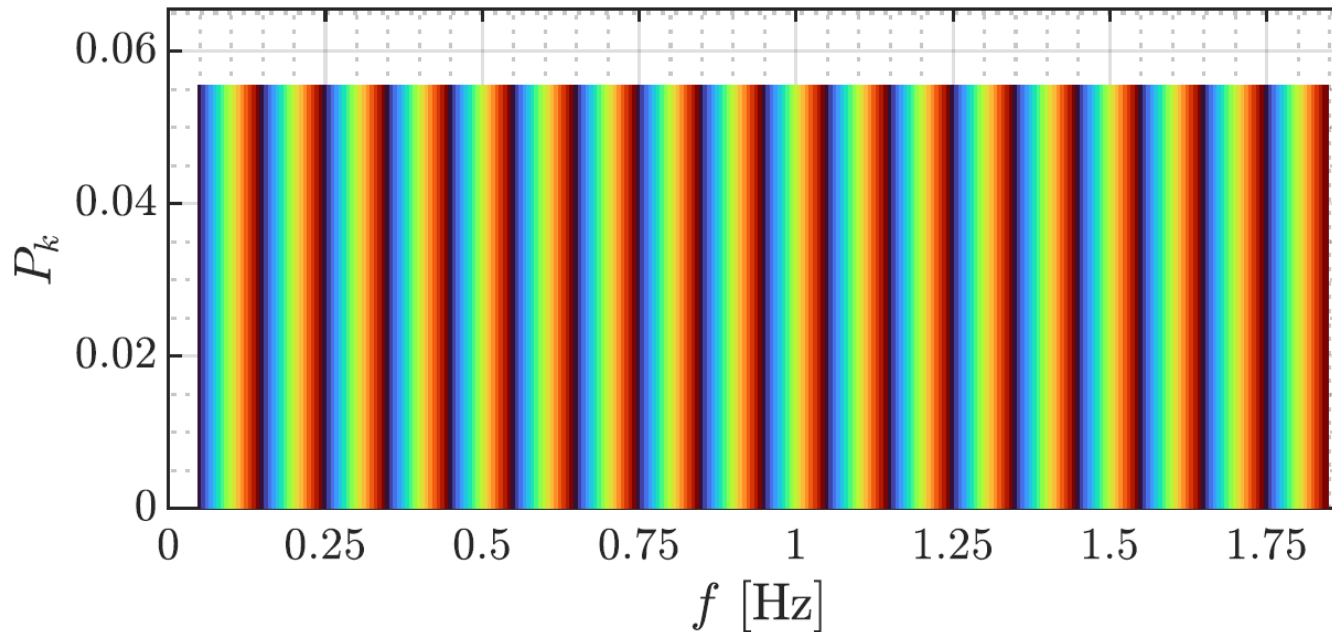
$u_j(t)$ – j th multisine signal

A – signal amplitude

P_k – k th power fraction

T – fundamental period

ϕ_k – k th phase angle



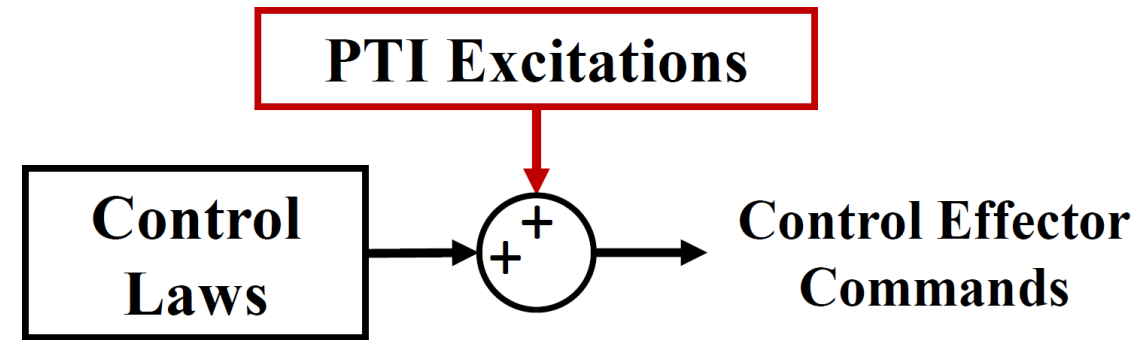
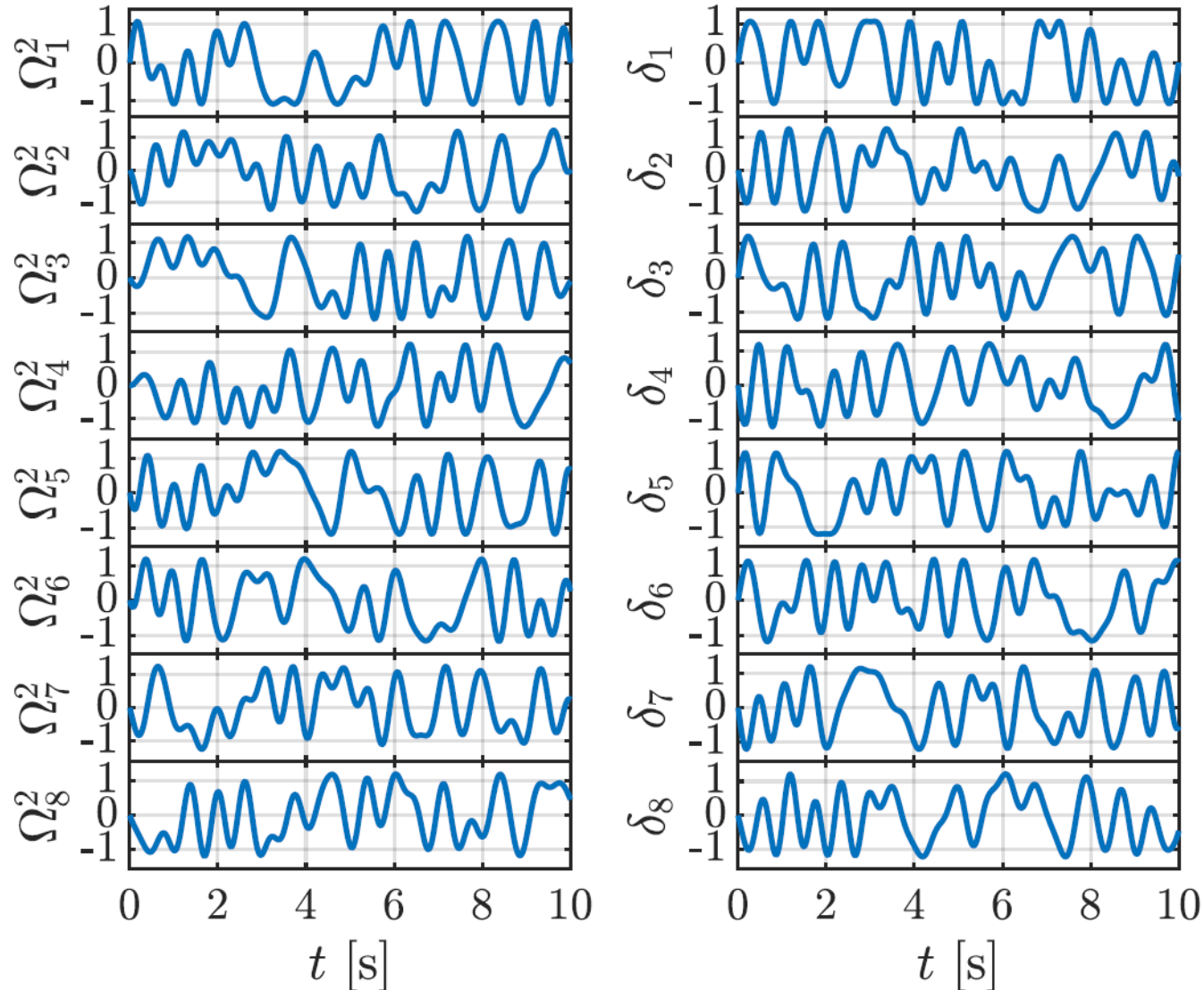
Note: Squared proprotor speed commands

AIBOT 500 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.

AIBOT 500 Multisine Inputs Signals



Multisine PTI injection location.

Normalized control effector multisine inputs.

Flight-Test Risk Reduction

- Multisine inputs successfully and safely applied in many vehicles¹
- New eVTOL vehicle applications

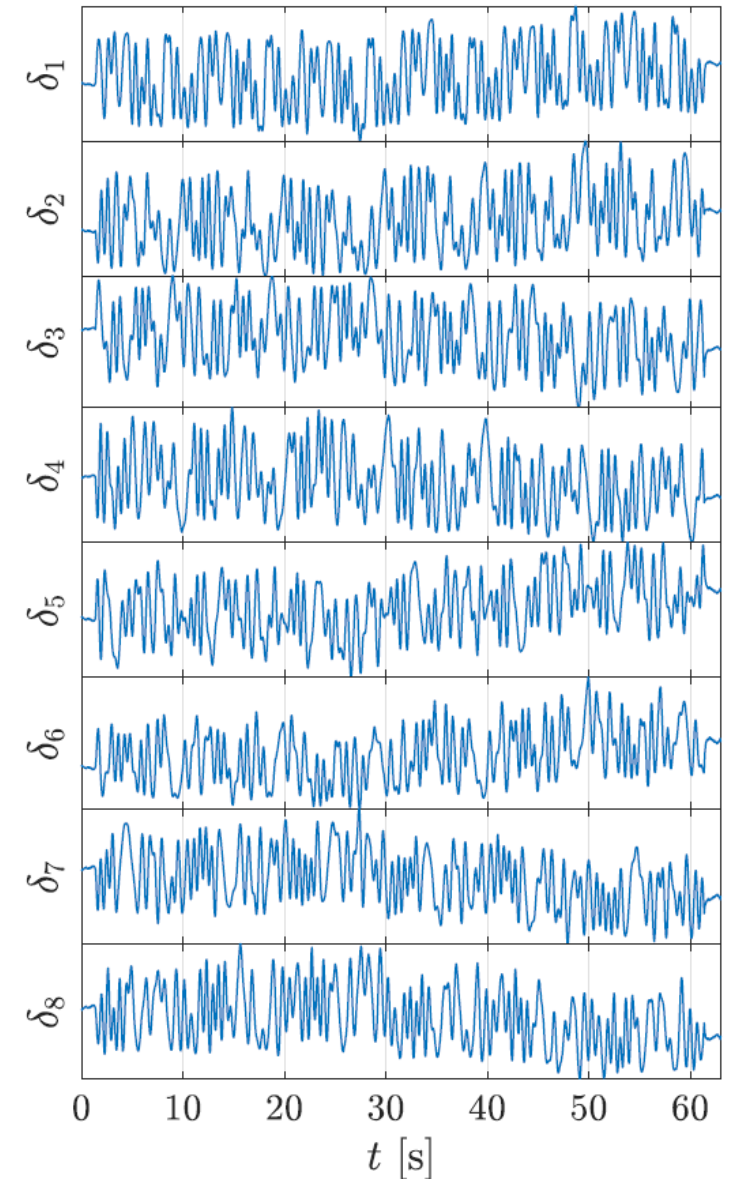
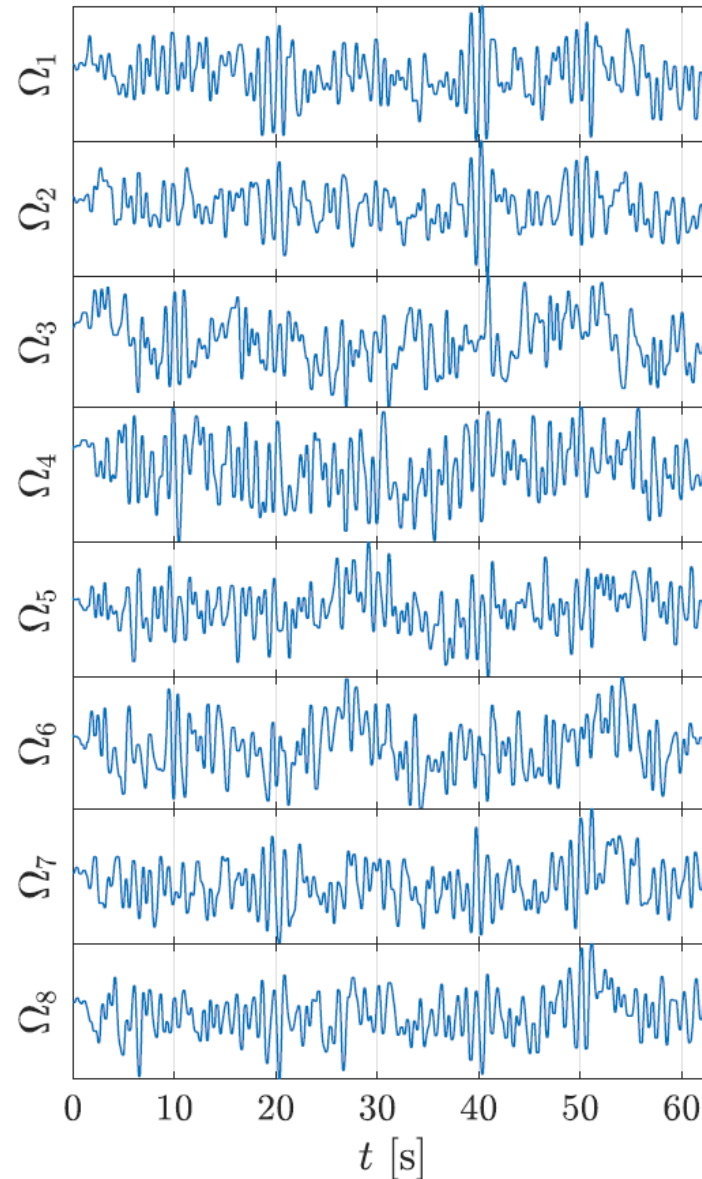
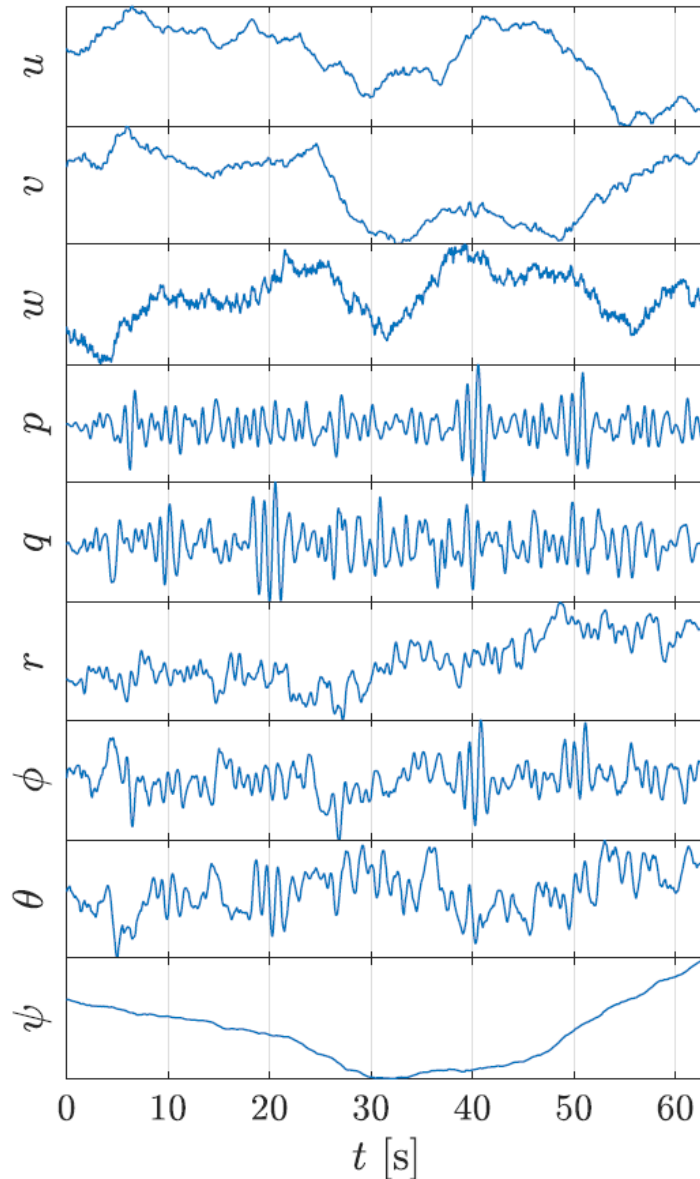
Steps taken to ensure safety of flight:

- Thrust stand testing (with and without control system in the loop)
- Execution of flight simulations
- Full-vehicle hardware-in-the-loop ground testing
- Multisine gains started low and gradually increased

1. Morelli, E. A., and Grauer, J. A., “Advances in Aircraft System Identification at NASA Langley Research Center,” *Journal of Aircraft*, Vol. 60, No. 5, 2023, pp. 1354–1370. <https://doi.org/10.2514/1.C037274>.

Hover Multisine Maneuver

Vertical scales are removed to protect proprietary vehicle information.



Model Identification Approach

- Aero-propulsive modeling framework tailored to eVTOL aircraft¹
- Explanatory variables:
 - Body-axis velocity components (u, v, w) and angular rates (p, q, r)
 - Squared proprotor rotational speeds ($\Omega_1^2, \Omega_2^2, \dots, \Omega_8^2$) →
 - Control surface deflection angles ($\delta_1, \delta_2, \dots, \delta_8$)
- 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: stepwise regression²
 - Parameter estimation: complex least-squares regression²

Linear thrust changes
 $T = \rho A (\Omega R)^2 C_T$

u, v, w, p, q, r
 $\Omega_1^2, \Omega_2^2, \dots, \Omega_8^2$
 $\delta_1, \delta_2, \dots, \delta_8$

**Aero-Propulsive
Model**

X, Y, Z, L, M, N

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. <https://doi.org/10.2514/1.C036351>.
2. Morelli, E. A., and Klein, V., *Aircraft System Identification: Theory and Practice*, 2nd ed., Sunflyte Enterprises, Williamsburg, VA, 2016.

Hover Model Structure

- Linear response surface model (can be extended to be nonlinear)
- Single parameter estimate for mirroring control effectors

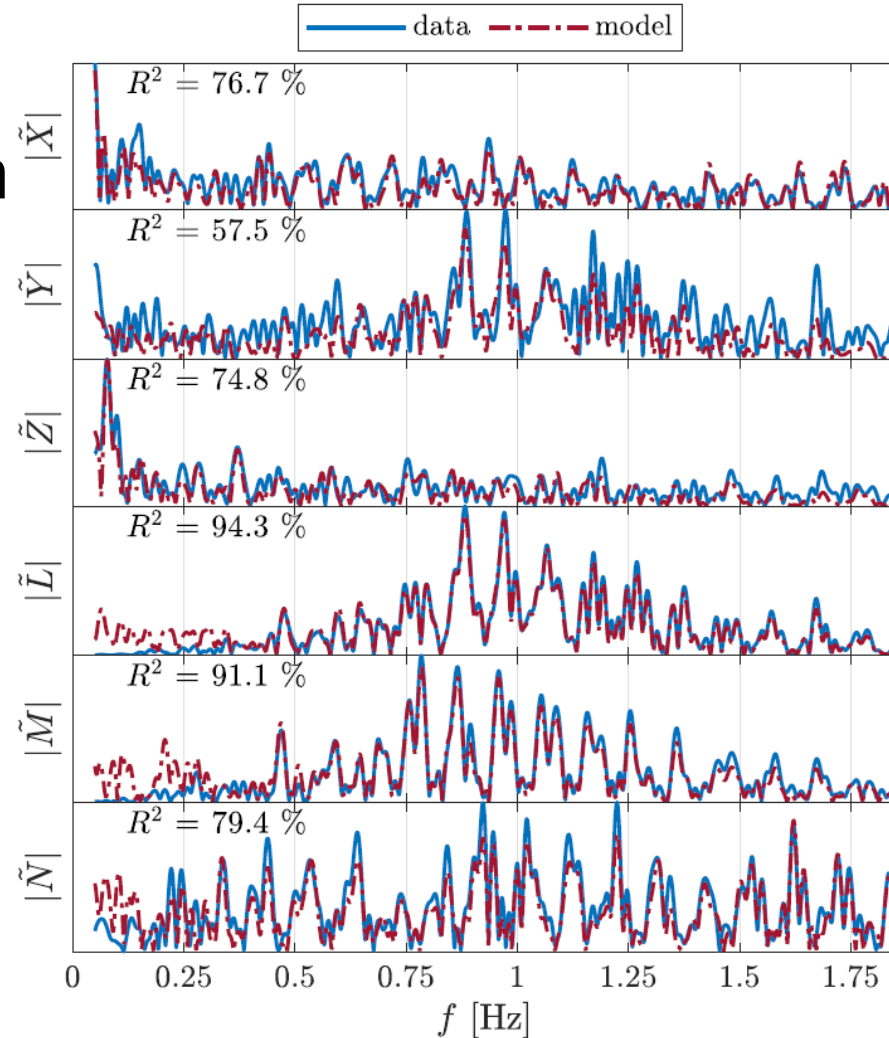
State derivatives

Control derivatives

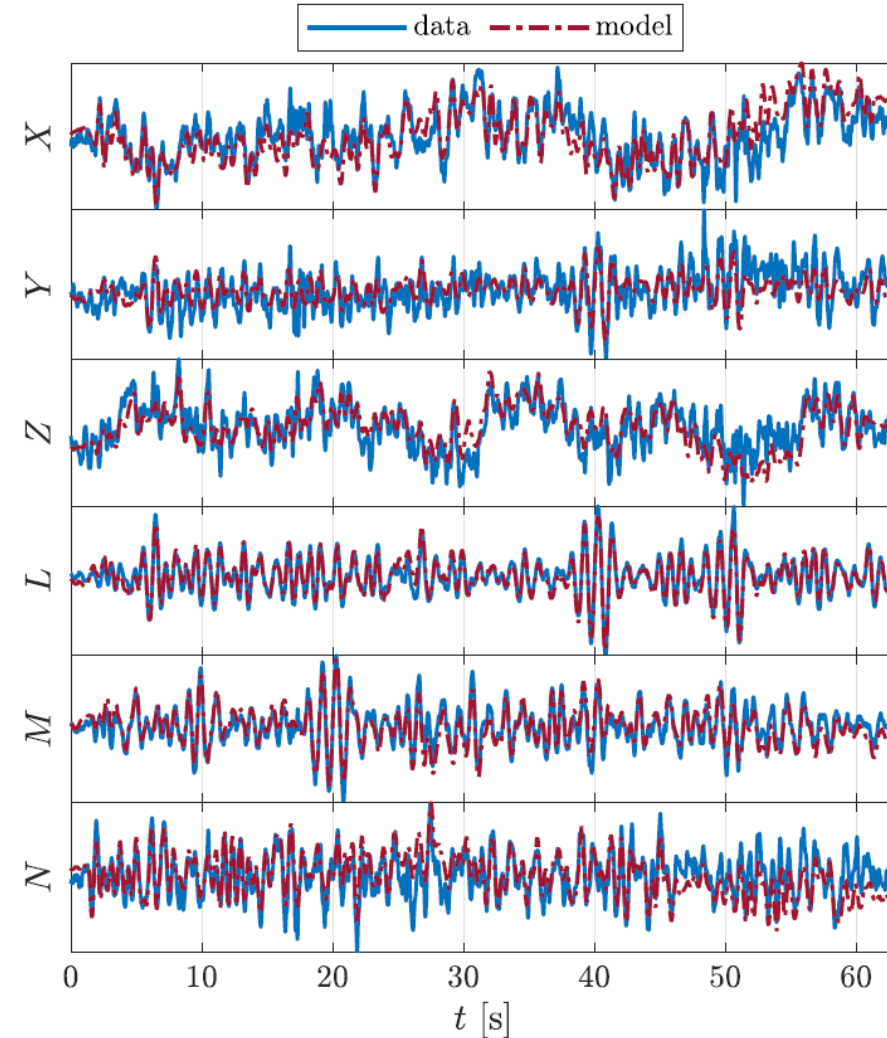
$$\begin{aligned}
 X &= \overbrace{X_u u + X_w w + X_q q}^{\text{State derivatives}} + \overbrace{X_{\delta_{14}}(\delta_1 + \delta_4) + X_{\delta_{23}}(\delta_2 + \delta_3) + X_{\delta_{58}}(\delta_5 + \delta_8) + X_{\delta_{67}}(\delta_6 + \delta_7)}^{\text{Control derivatives}} + X_o \\
 Y &= Y_v v + Y_p p + Y_r r + Y_{\Omega_{14}^2}(\Omega_1^2 - \Omega_4^2) + Y_{\Omega_{23}^2}(\Omega_2^2 - \Omega_3^2) + Y_{\Omega_{58}^2}(\Omega_5^2 - \Omega_8^2) + Y_{\Omega_{67}^2}(\Omega_6^2 - \Omega_7^2) + Y_o \\
 Z &= Z_u u + Z_w w + Z_q q + Z_{\Omega_{14}^2}(\Omega_1^2 + \Omega_4^2) + Z_{\Omega_{23}^2}(\Omega_2^2 + \Omega_3^2) + Z_{\Omega_{58}^2}(\Omega_5^2 + \Omega_8^2) + Z_{\Omega_{67}^2}(\Omega_6^2 + \Omega_7^2) + Z_o \\
 L &= L_v v + L_p p + L_r r + L_{\Omega_{14}^2}(\Omega_1^2 - \Omega_4^2) + L_{\Omega_{23}^2}(\Omega_2^2 - \Omega_3^2) + L_{\Omega_{58}^2}(\Omega_5^2 - \Omega_8^2) + L_{\Omega_{67}^2}(\Omega_6^2 - \Omega_7^2) + L_o \\
 M &= M_u u + M_w w + M_q q + M_{\Omega_{14}^2}(\Omega_1^2 + \Omega_4^2) + M_{\Omega_{23}^2}(\Omega_2^2 + \Omega_3^2) + M_{\Omega_{58}^2}(\Omega_5^2 + \Omega_8^2) + M_{\Omega_{67}^2}(\Omega_6^2 + \Omega_7^2) + M_o \\
 N &= N_v v + N_p p + N_r r + N_{\delta_{14}}(\delta_1 - \delta_4) + N_{\delta_{23}}(\delta_2 - \delta_3) + N_{\delta_{58}}(\delta_5 - \delta_8) + N_{\delta_{67}}(\delta_6 - \delta_7) + N_o
 \end{aligned}$$

Initial Hover Modeling Results

- Complex least-squares regression
- Good model fit for L and M
- Adequate model fit for X , Z , and N
- Lower quality model fit for Y (no direct excitation)



Frequency domain

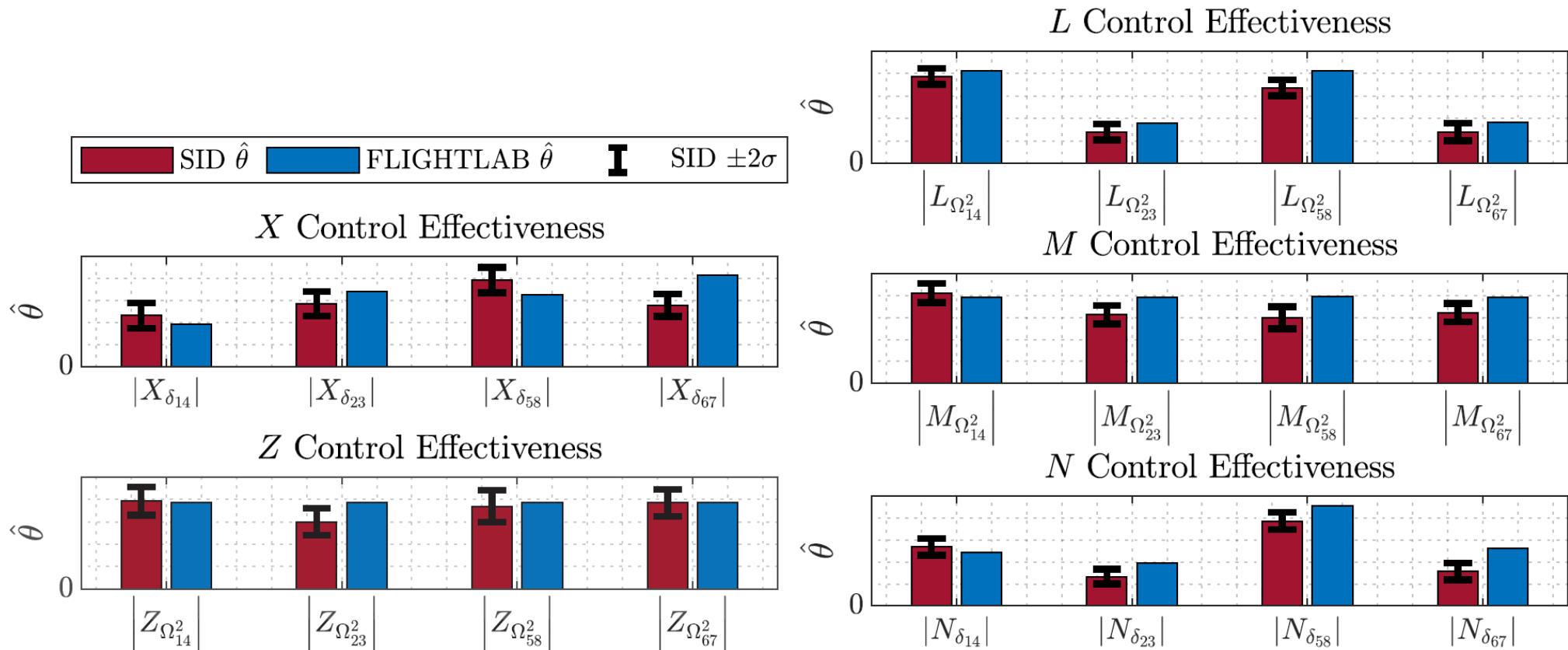


Time domain

Comparison of modeling response data and model fit.

Initial Hover Parameter Estimates

- Control derivative parameters accurately identified (4% to 15% errors)
- State derivative parameters had higher uncertainty estimates



Control effectiveness parameters derived from system identification (SID) and FLIGHTLAB®.

Lessons Learned from Recent Testing

- Additional state perturbations may be required at low speeds¹
- Flight-test strategy modified for April 2025 hover system identification flights (just before the VFS paper submission deadline)
 - Multisine inputs active on each control effector
 - and**
 - Pilot commands doublet inputs in each axis during the multisine maneuver
- State derivative identification accuracy substantially improves
- Model fit substantially improves
- New results are described qualitatively in the paper

1. Simmons, B. M., Ackerman, K. A., and Asper, G. D., “Aero-Propulsive Damping Characterization for eVTOL Aircraft Using Free Motion Wind-Tunnel Testing,” *AIAA SciTech 2025 Forum*, January 2025. <https://doi.org/10.2514/6.2025-0006>.



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

Benjamin M. Simmons and Kasey A. Ackerman

NASA Langley Research Center

AIAA SciTech Forum

12–16 January 2026

RAVEN-SWFT

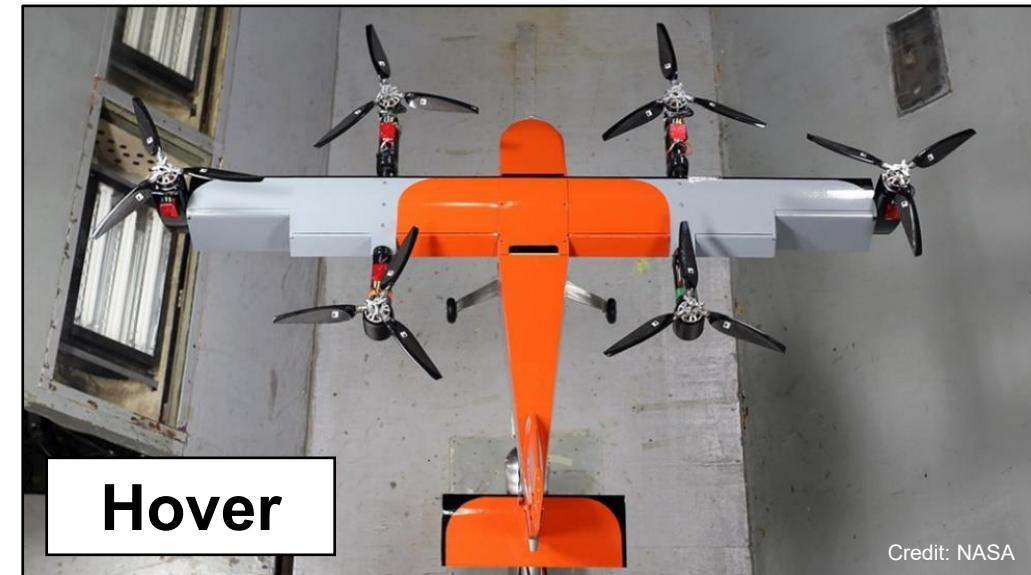
Research Aircraft for eVTOL Enabling TechNologies (RAVEN)¹
Subscale Wind-Tunnel and Flight Test (SWFT) Vehicle²



- 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 ($n_1, n_2, \dots, n_6$)
 - Six collective angles ($\delta_{c_1}, \delta_{c_2}, \dots, \delta_{c_6}$)
 - Four nacelle tilt angles ($\delta_{t_1}, \delta_{t_2}, \delta_{t_3}, \delta_{t_4}$)
 - Six flaperons ($\delta_{f_1}, \delta_{f_2}, \dots, \delta_{f_6}$)
 - 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/>

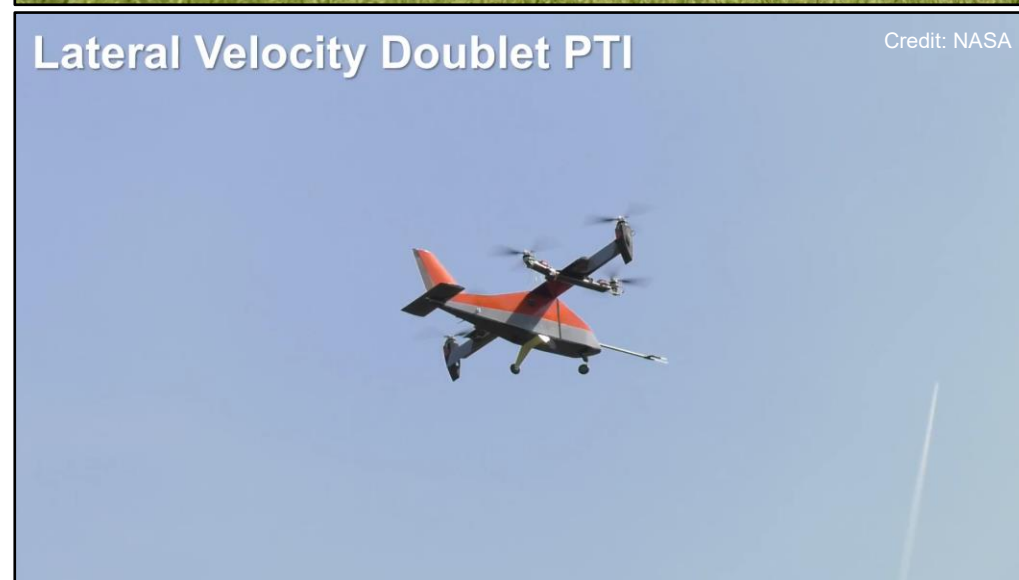
2. Geuther, S. C., Simmons, B. M., and Ackerman, K. A., "Overview of the Subscale RAVEN Flight Controls and Modeling Testbed," *VFS Forum 80*, May 2024.



RAVEN-SWFT Development and Testing



- Baseline wind-tunnel testing¹
 - Isolated proprotor test
 - Static full-airframe test
 - Dynamic 3DOF free-motion test
- Custom unified flight control algorithm¹
 - 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

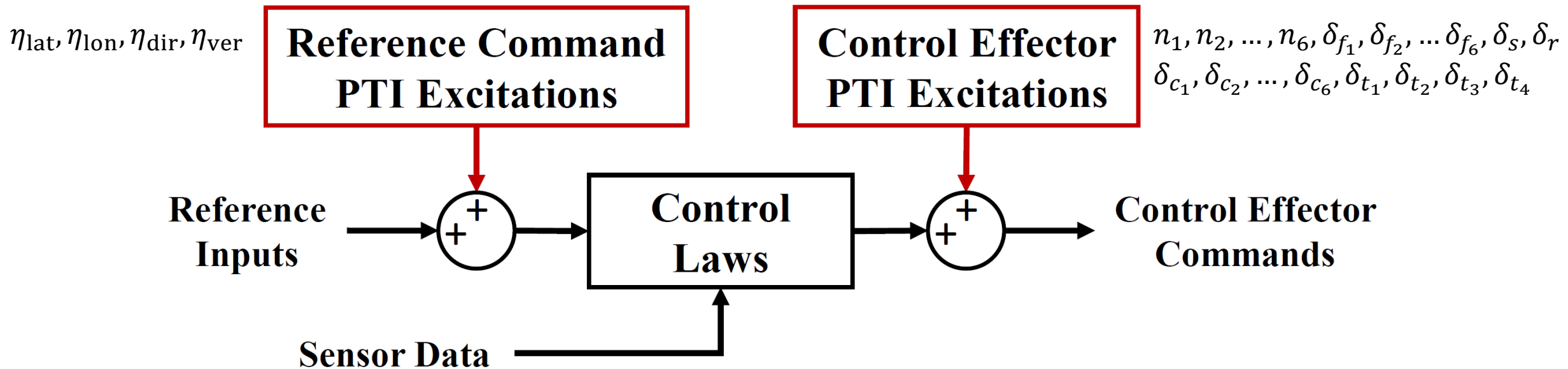


1. Simmons, B. M., Ackerman, K. A., Asper, G. D., Gray, M. N., Snyder, S. M., Axten, R. M., Geuther, S. C., and Chan, R., "Subscale Tiltrotor eVTOL Aircraft Dynamic Modeling and Flight Control Software Development," *VFS Annual Forum*, May 2025.

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

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

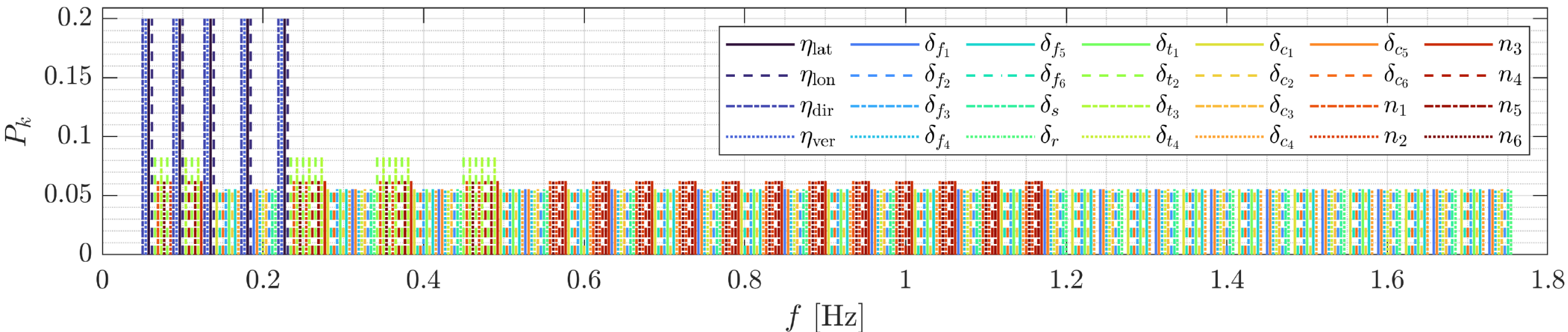
$u_j(t)$ – j th multisine signal

A – signal amplitude

P_k – k th power fraction

T – fundamental period

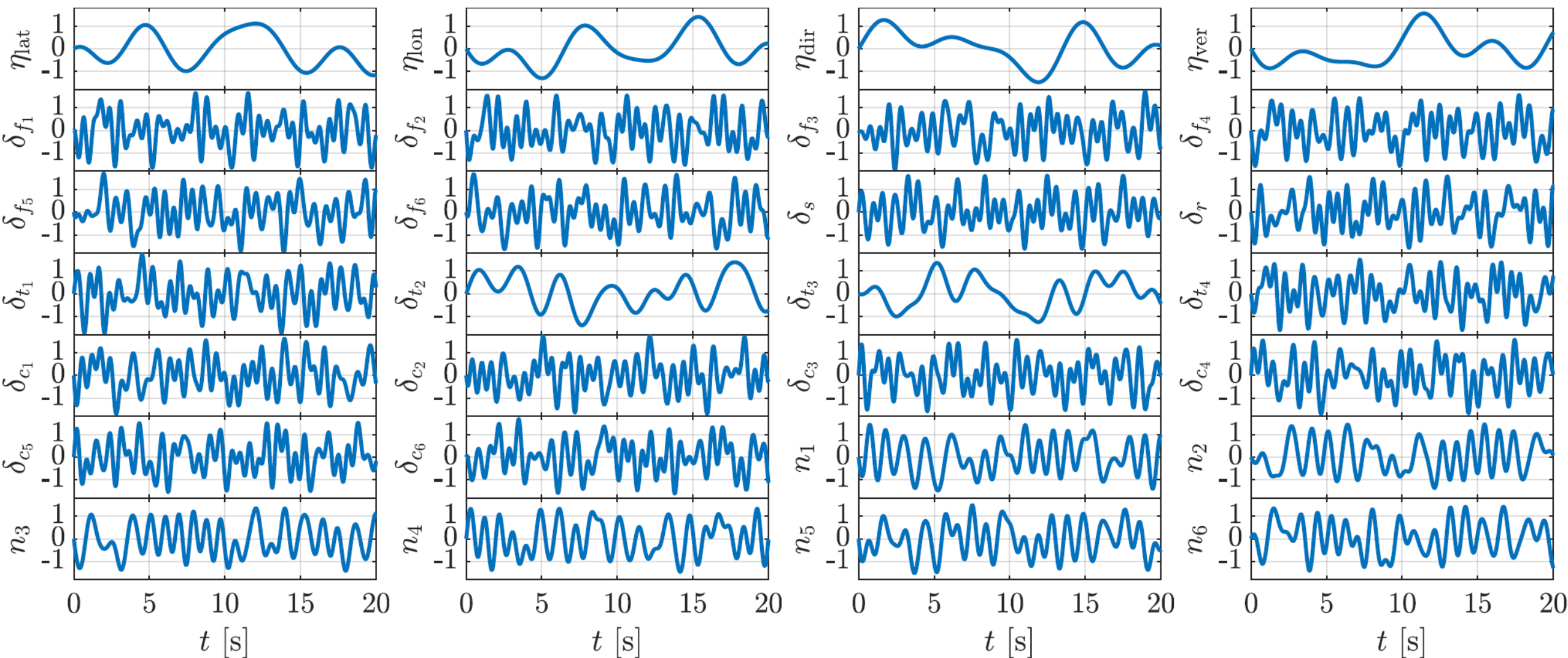
ϕ_k – k th phase angle



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.

Simmons and Ackerman, NASA Langley



Hover RC+CE multisine maneuver.

AIAA SciTech Forum – January 2026

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

CE Multisine PTI

Credit: NASA



RC+CE Multisine PTI

Credit: NASA



Model Identification Approach



- Aero-propulsive modeling framework tailored to eVTOL aircraft¹
- 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 speeds² ($n_1^2, n_2^2, \dots, n_6^2$) $\longrightarrow$ 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 regression³
 - Final parameter estimates computed using multiple maneuvers

$u, v, w, \dot{u}, \dot{v}, \dot{w}$
 p, q, r
 $n_1^2, n_2^2, \dots, n_6^2$
 $\delta_{c_1}, \delta_{c_2}, \dots, \delta_{c_6}$
 $\delta_{t_1}, \delta_{t_2}, \delta_{t_3}, \delta_{t_4}$
 $\delta_{f_1}, \delta_{f_2}, \dots, \delta_{f_6}$
 δ_s, δ_r

Aero-Propulsive Model

X, Y, Z, L, M, N

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.

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

Simmons and Ackerman, NASA Langley

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Hover Model Structure



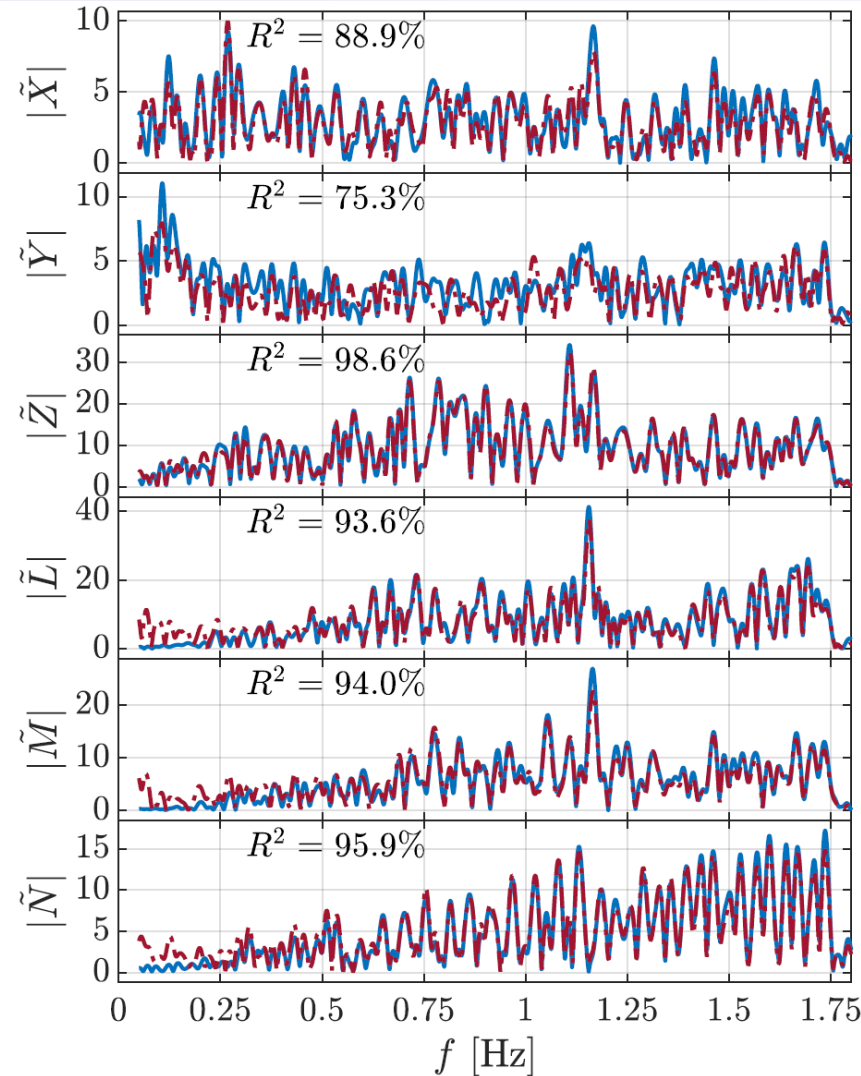
- Nonlinear terms considered/included
- Model parameter symmetrization

$$\begin{aligned}
 X &= X_u u + X_w w + X_{wq} wq + X_{\delta_{f16}} (\delta_{f1} + \delta_{f6}) + X_{\delta_{t14}} (\delta_{t1} + \delta_{t4}) + X_{\delta_{t23}} (\delta_{t2} + \delta_{t3}) + X_{\delta_{c23}} (\delta_{c2} + \delta_{c3}) \\
 &\quad + X_{\delta_{c56}} (\delta_{c5} + \delta_{c6}) + 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_{t1} + n_4^2 \delta_{t4}) + X_{n_{23}^2 \delta_{t23}} (n_2^2 \delta_{t2} + n_3^2 \delta_{t3}) \\
 &\quad + X_{\delta_{c14} \delta_{t14}} (\delta_{c1} \delta_{t1} + \delta_{c4} \delta_{t4}) + X_{\delta_{c23} \delta_{t23}} (\delta_{c2} \delta_{t2} + \delta_{c3} \delta_{t3}) + X_o \\
 Y &= Y_v v + Y_{\delta_{t14}} (\delta_{t1} - \delta_{t4}) + Y_{\delta_{t23}} (\delta_{t2} - \delta_{t3}) + Y_{\delta_{c14}} (\delta_{c1} - \delta_{c4}) + Y_{\delta_{c23}} (\delta_{c2} - \delta_{c3}) + Y_{\delta_{c56}} (\delta_{c5} - \delta_{c6}) \\
 &\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_{c1} + \delta_{c4}) + Z_{\delta_{c23}} (\delta_{c2} + \delta_{c3}) + Z_{\delta_{c56}} (\delta_{c5} + \delta_{c6}) + 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_{f1} - \delta_{f6}) + L_{\delta_{t14}} (\delta_{t1} - \delta_{t4}) + L_{\delta_{c14}} (\delta_{c1} - \delta_{c4}) + L_{\delta_{c23}} (\delta_{c2} - \delta_{c3}) \\
 &\quad + L_{\delta_{c56}} (\delta_{c5} - \delta_{c6}) + 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_{c2} + \delta_{c3}) + M_{\delta_{c56}} (\delta_{c5} + \delta_{c6}) \\
 &\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_{f1} - \delta_{f6}) + N_{\delta_{t14}} (\delta_{t1} - \delta_{t4}) + N_{\delta_{t23}} (\delta_{t2} - \delta_{t3}) + N_{\delta_{c14}} (\delta_{c1} - \delta_{c4}) + N_{\delta_{c23}} (\delta_{c2} - \delta_{c3}) \\
 &\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_{t1} - n_4^2 \delta_{t4}) + N_{\delta_{c14} \delta_{t14}} (\delta_{c1} \delta_{t1} - \delta_{c4} \delta_{t4}) + I_p (\sum_{i=1}^6 (-1)^i \dot{\Omega}_i)
 \end{aligned}$$

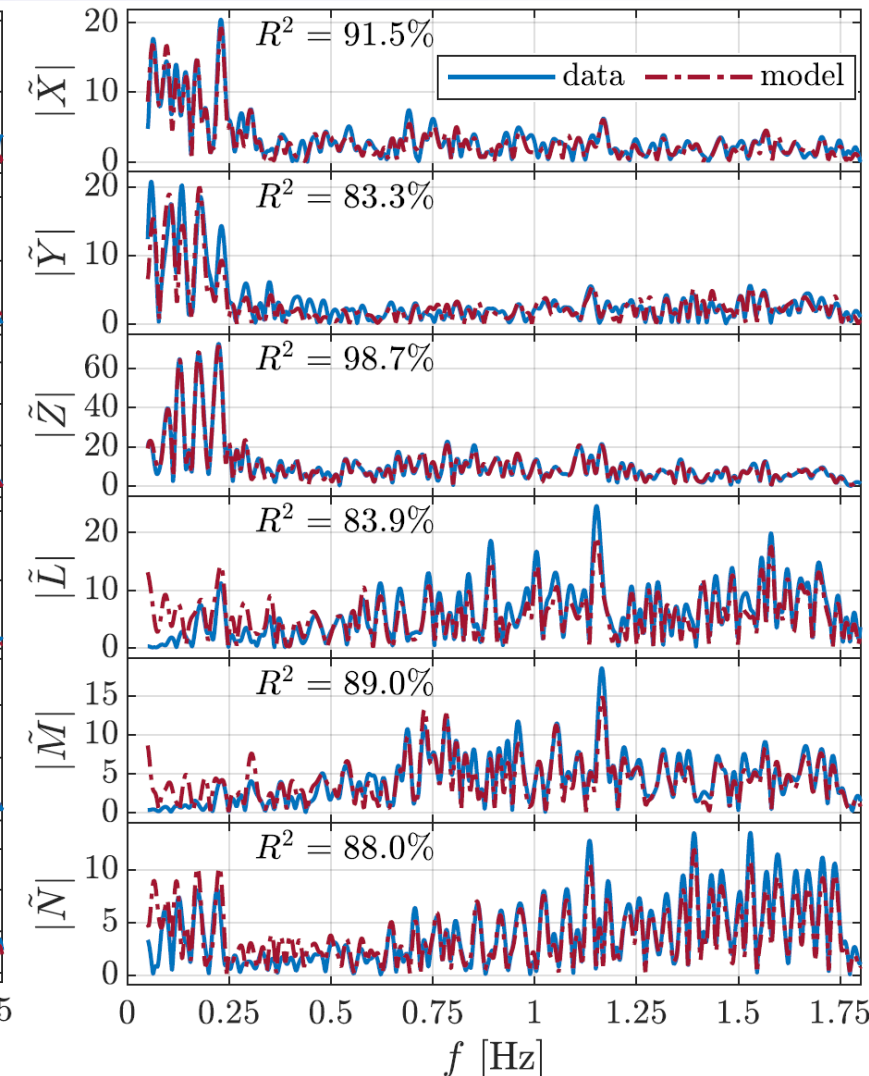
Frequency-Domain Hover Modeling Results



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



CE multisine maneuver



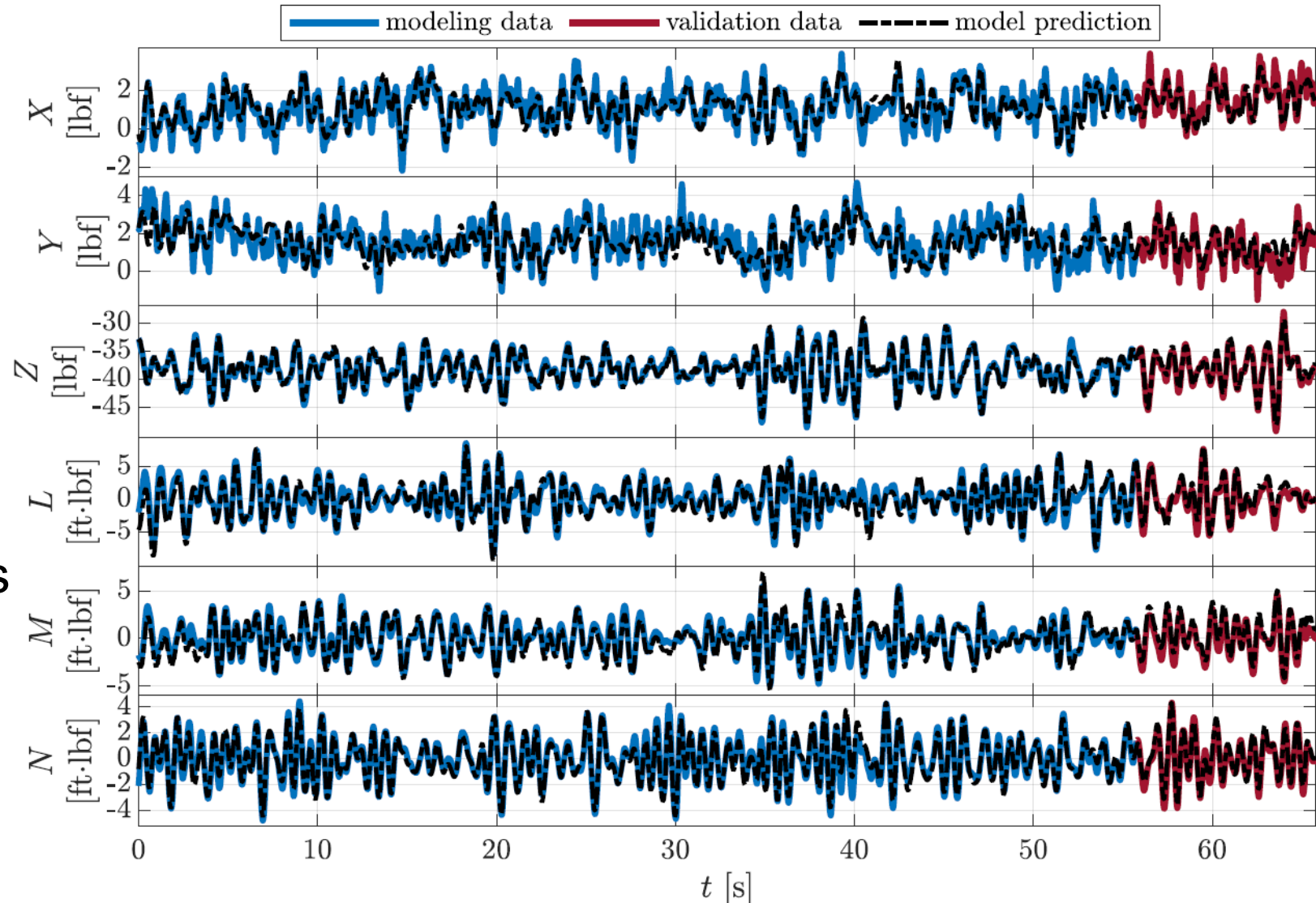
RC+CE multisine maneuver

Comparison of response data and model fit for example maneuvers.

Hover 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

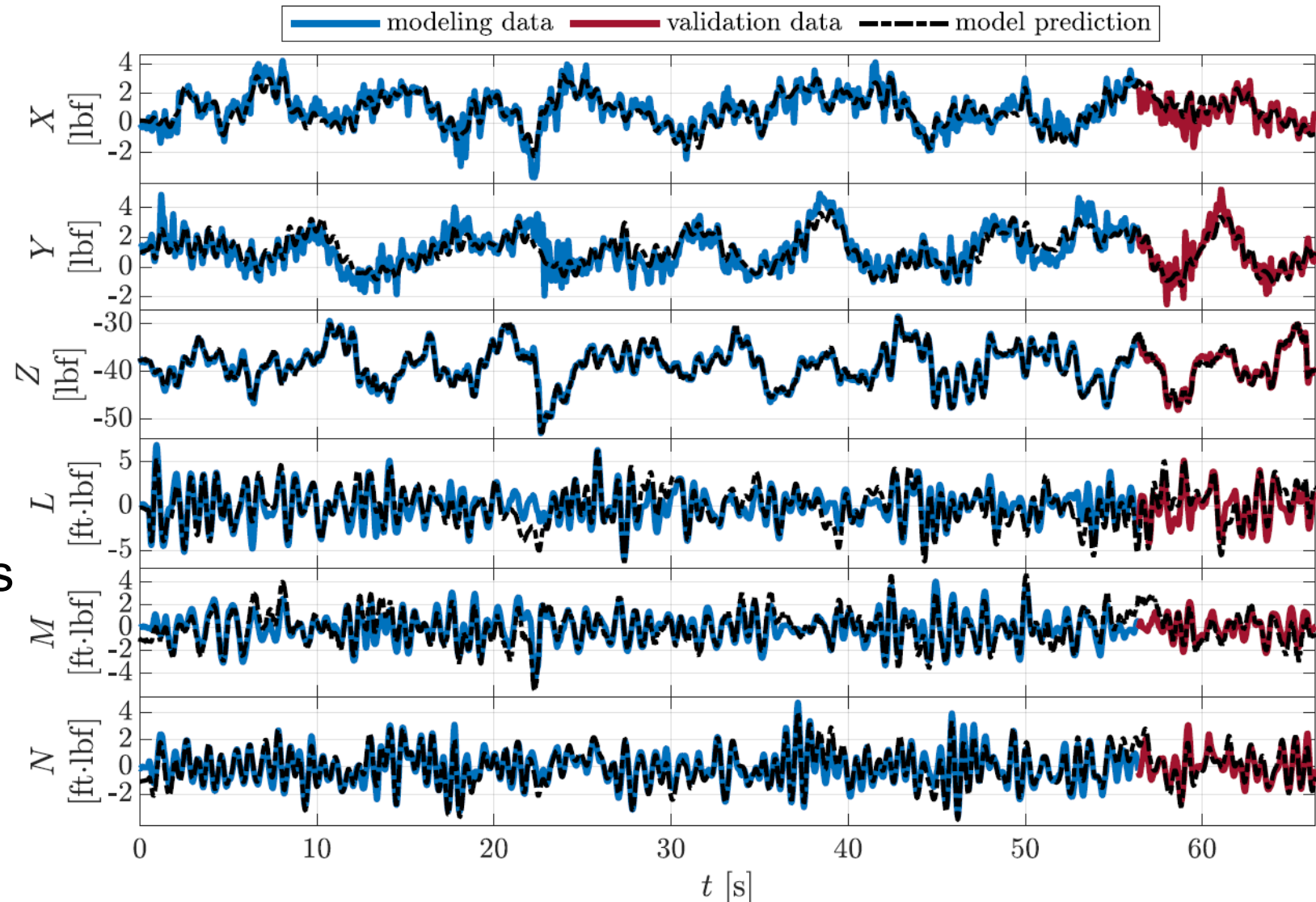


Comparison of response data and model prediction.

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.

Conclusions and Next Steps

Concluding Remarks



- eVTOL aircraft present new system identification challenges
- Efficient maneuvers employing orthogonal phase-optimized multisine inputs
- Demonstration of the utility and efficiency of the modeling approach
 - Quick, accurate identification of all stability and control derivatives
 - Assessment and identification of nonlinear model terms, if needed
 - Minimal additional risk posed to the vehicle
- Programmed test input injections before and after the control laws are important
- Techniques can be applied throughout transition and for many vehicles



RAVEN-SWFT system ID maneuver.

Next Steps



- Flight-test system identification in transition and forward flight
- NASA RAVEN 1000-lb-class vehicle
 - Research platform providing open geometry, data, and methods
 - Tiltrotor configuration relevant to eVTOL vehicles being developed in industry
 - Initial research emphasis on aero-propulsive characterization, flight controls, and acoustics
- Active research is further refining eVTOL vehicle modeling techniques
- Open to establishing additional collaboration opportunities



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Questions/Discussion

Thank you for attending.

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