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

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Contents

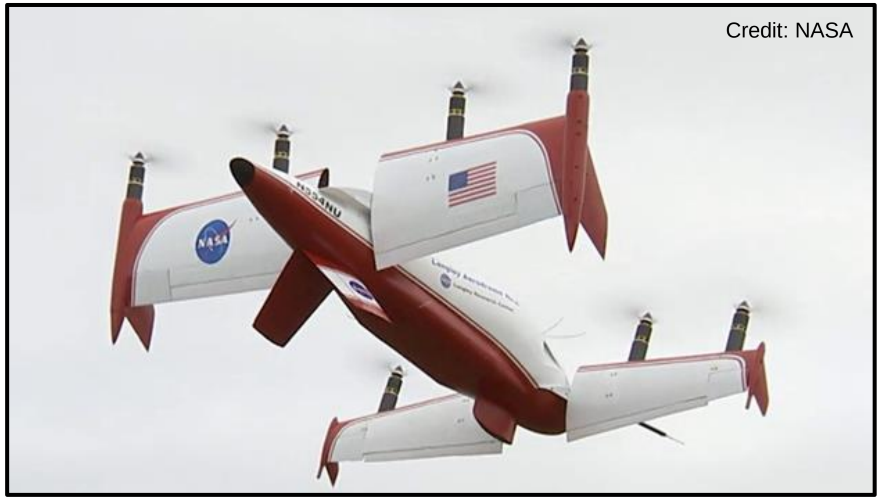
- Motivation
- Background
- Aircraft
- System identification approach
- Hover flight-test results
- Lessons learned
- Concluding remarks
- Questions

Research Motivation

- Technology advances enabling practical electric vertical takeoff and landing (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 testing and modeling strategies for eVTOL aircraft to efficiently deliver high-fidelity aero-propulsive models

NASA RAVEN-SWFT aircraft

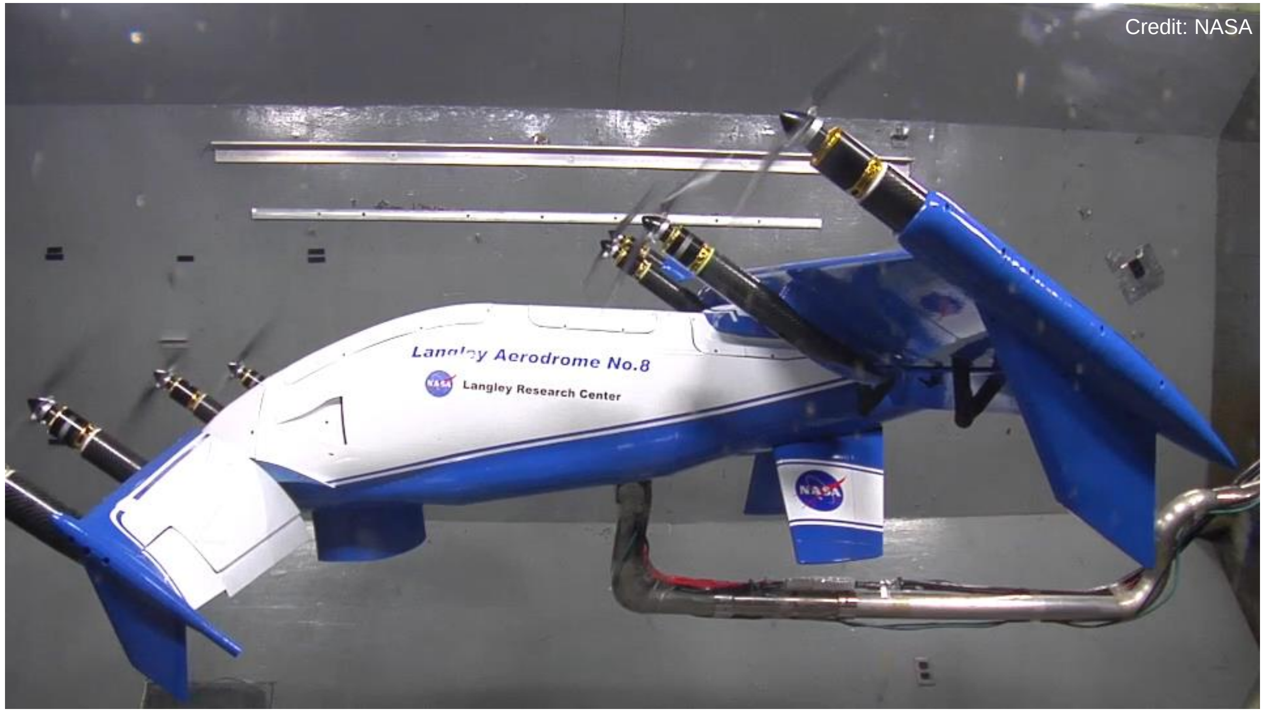


NASA LA-8 aircraft

Advanced Air Mobility (AAM)

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

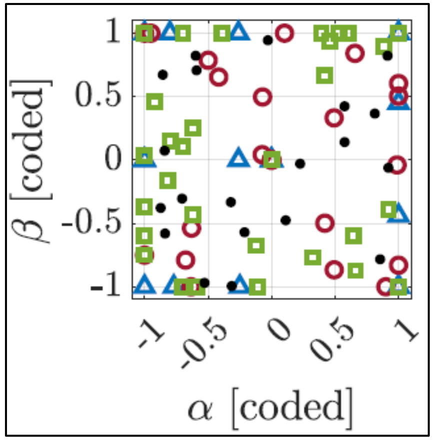


LA-8 DOE/RSM wind-tunnel testing.

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.

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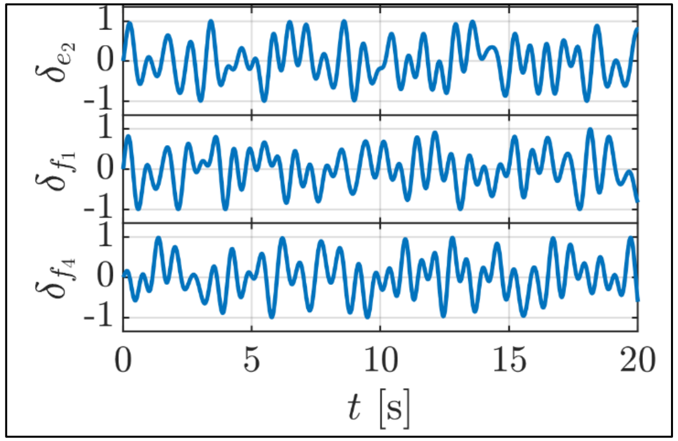


Sample multisine PTI signals.

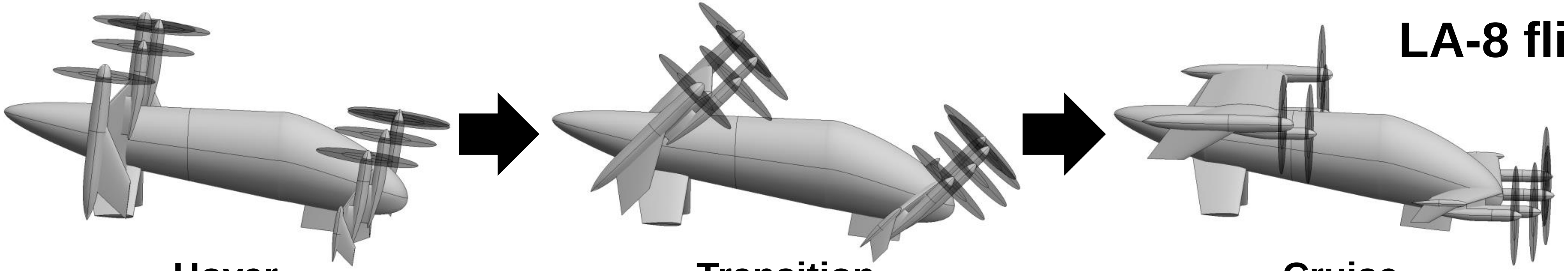
Hybrid DOE/RSM+PTI testing.

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.

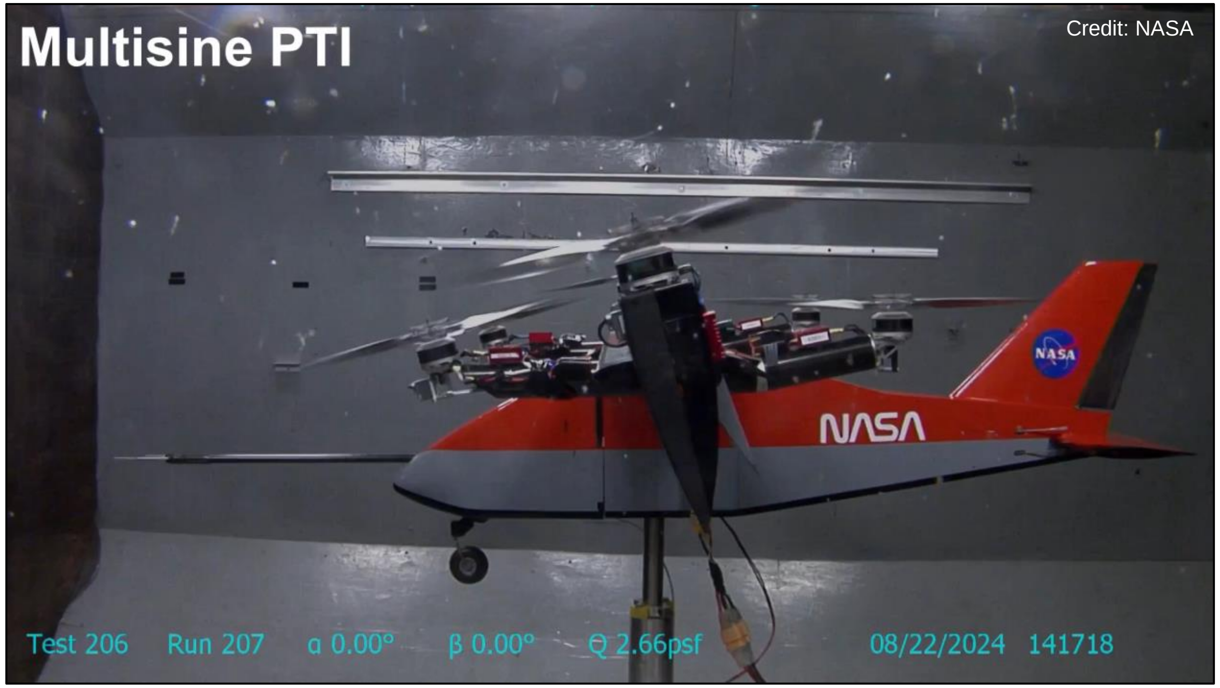


Complements safe envelope expansion flight testing

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," *AIAA SciTech 2025 Forum*, Jan. 2025. https://doi.org/10.2514/6.2025-0006.

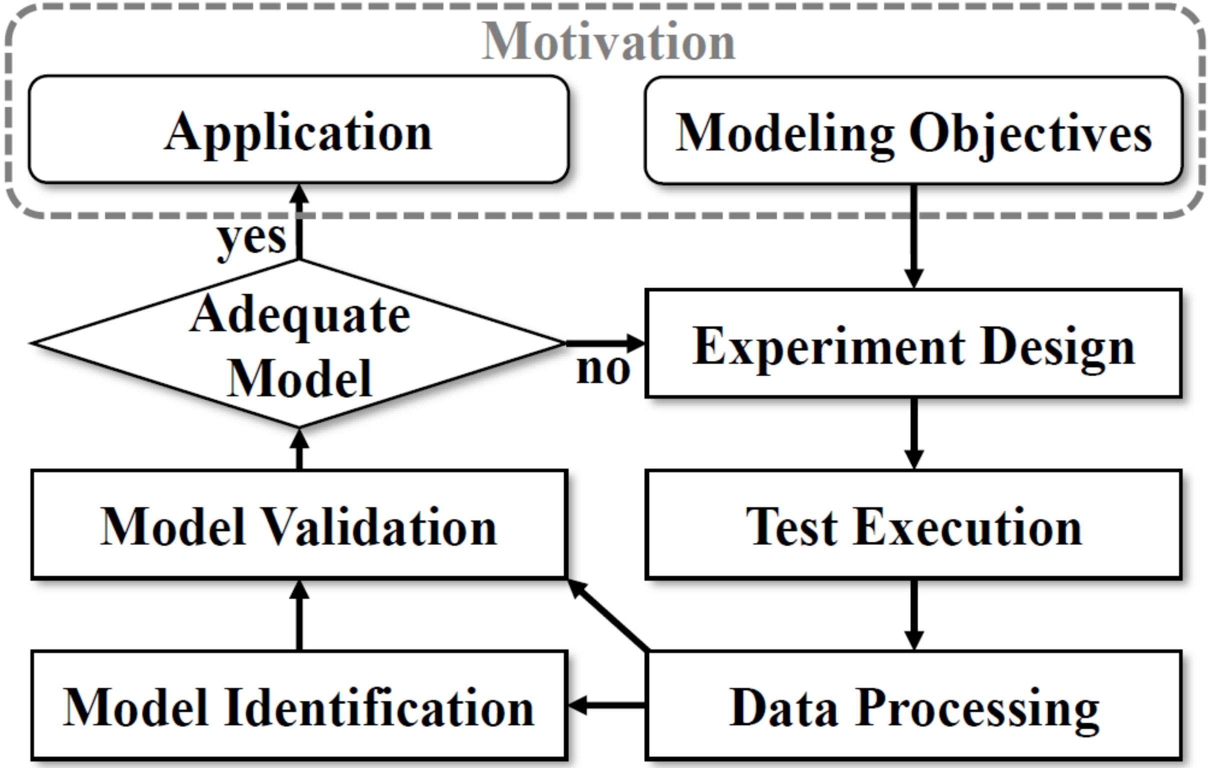
Aircraft: AIBOT 500

- AIBOT prototype 500-lb aircraft
- Transitioning, vectored-thrust, eVTOL configuration
- 8 proprotors ($\Omega_1, \Omega_2, \ldots, \Omega_8$)
- 8 control surfaces ($\delta_1, \delta_2, \ldots, \delta_8$)
- Proprotor-control surface interactions in all phases of flight
- AIBOT 500 configuration is **<u>not</u>** 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

System Identification Approach

- Development of a mathematical model from flight data
- Present motivation:
  - Computational tool validation
  - Simulation for control law design
- Desired attributes:
  - Open-loop model identification
  - Efficient flight-test execution
  - Determine the independent effectiveness of all controls
  - Include nonlinear aerodynamics and control interaction effects, if needed
- System IDentification Programs for AirCraft (SIDPAC)[1] software

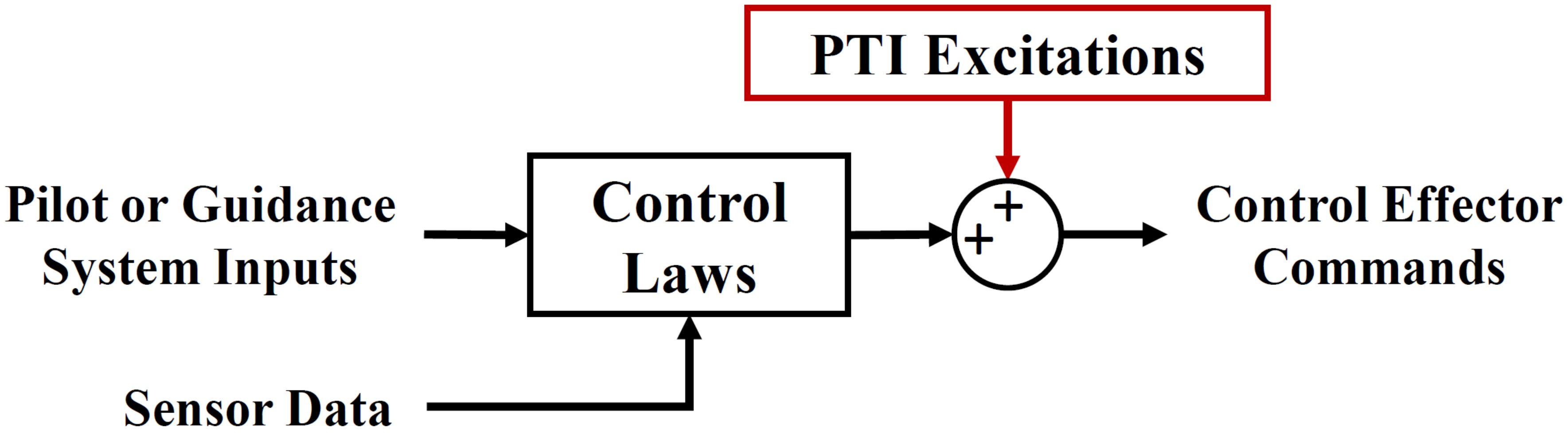


General system identification process.

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

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



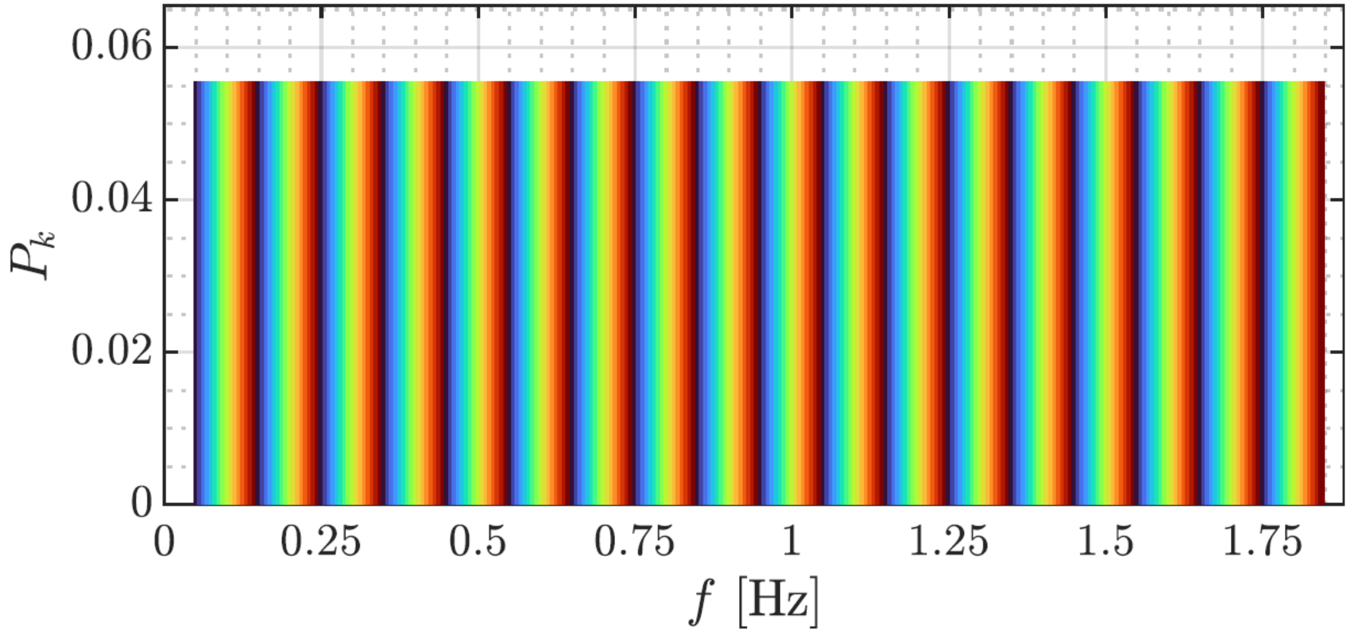
PTI injections relative to the control laws.

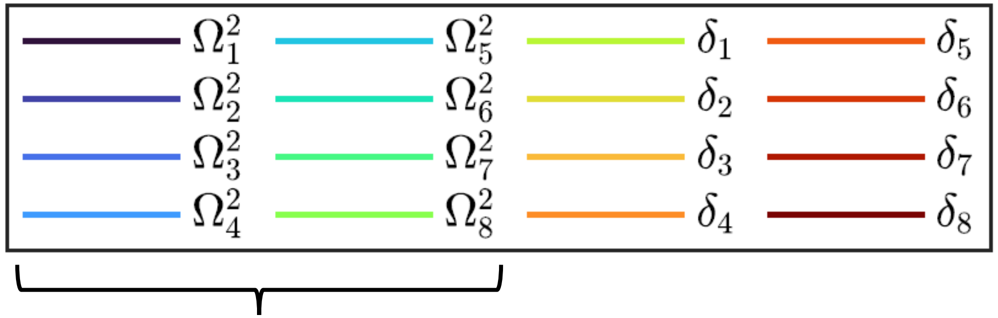
Input Design

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

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

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



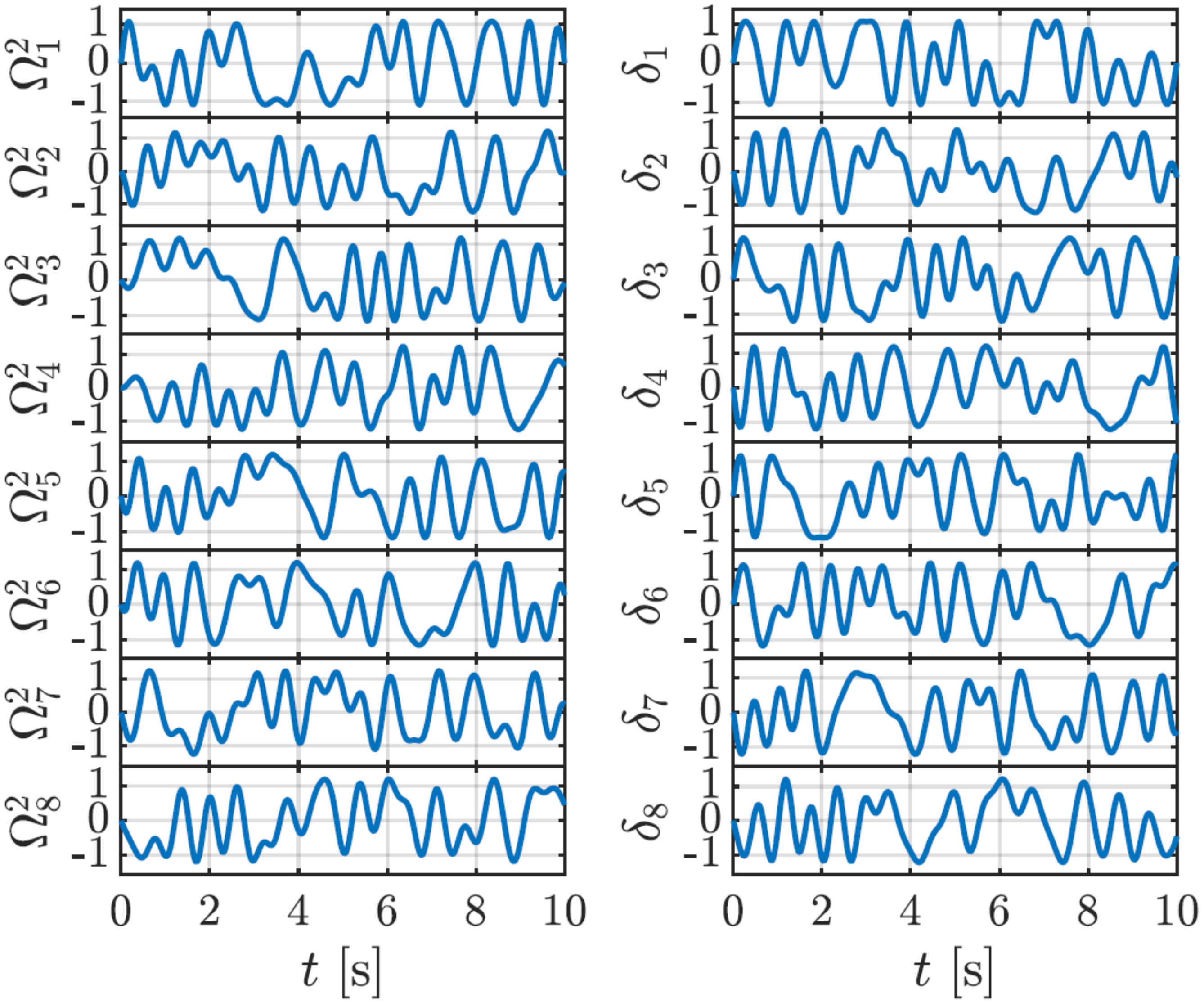


Note: *Squared* proprotor speed commands

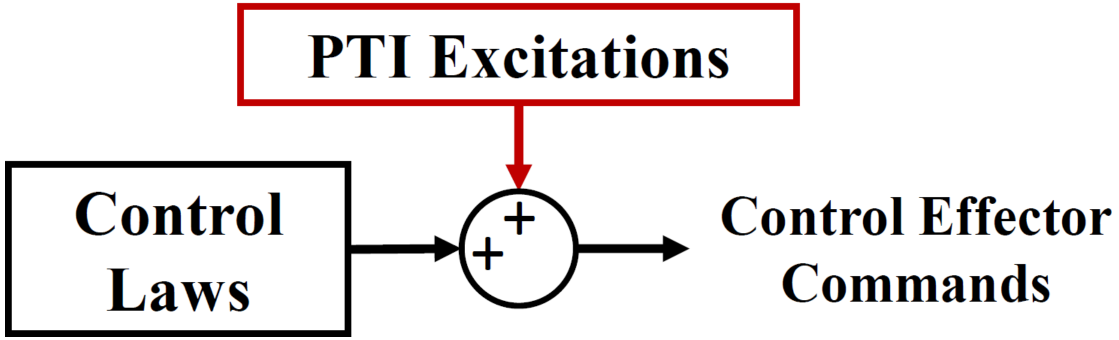
AIBOT 500 vehicle multisine input spectra.

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



Normalized control effector multisine inputs.



Multisine PTI injection location.

Flight-Test Risk Reduction

- Multisine inputs successfully and safely applied in many vehicles[1]
- New eVTOL vehicle applications

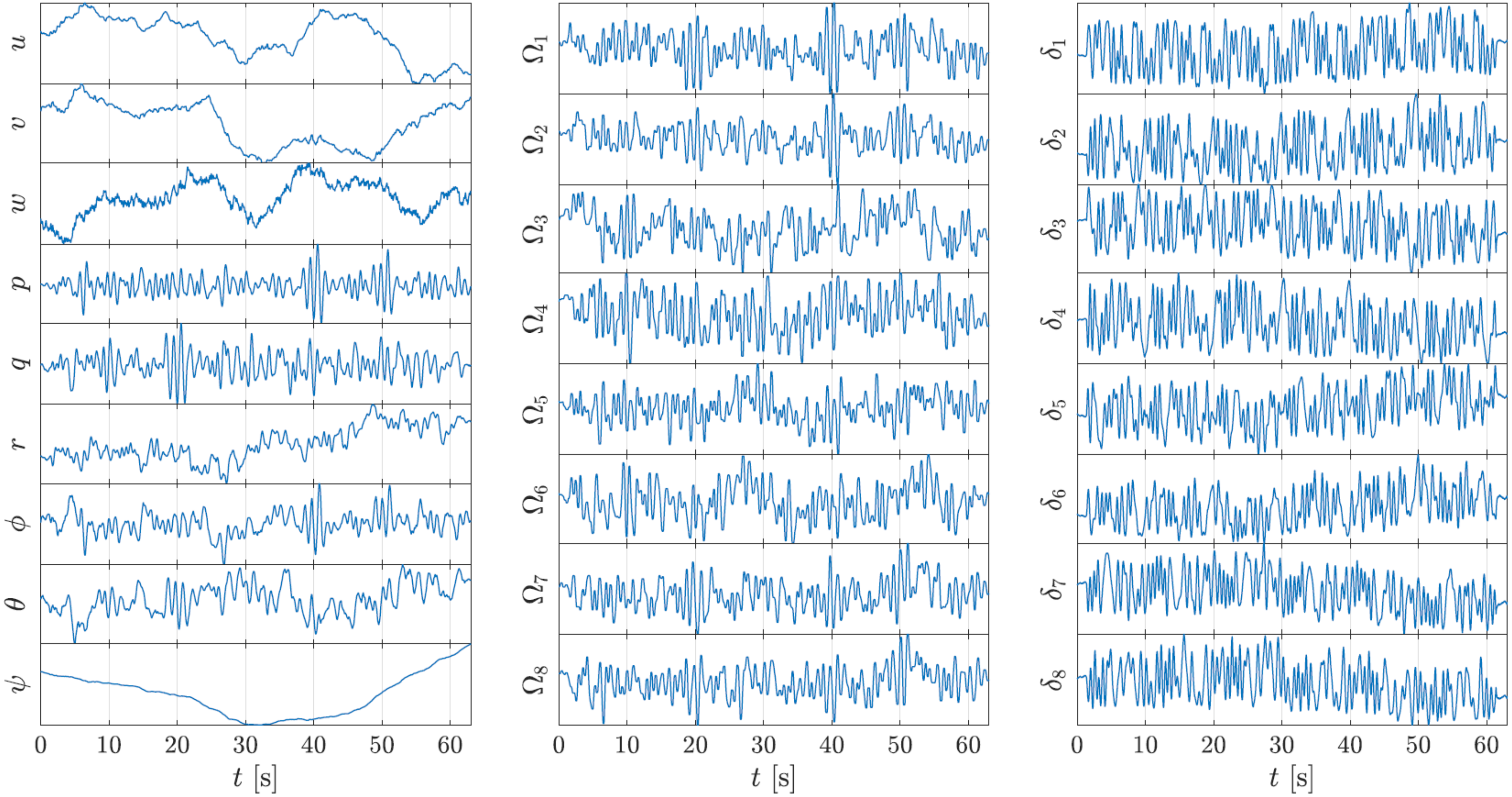
Steps taken to ensure safety of flight:

- 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.

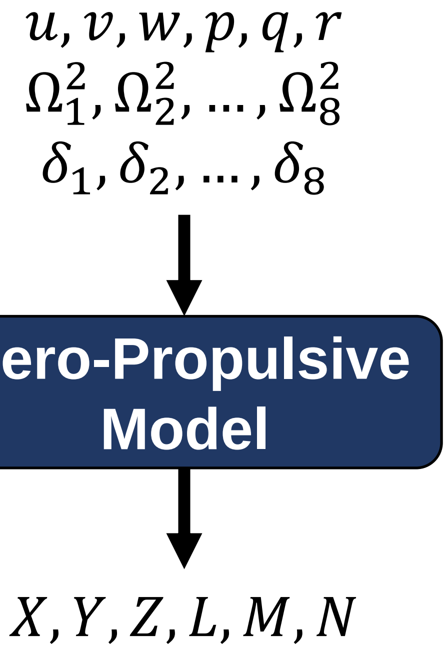
Hover Multisine Maneuver

Vertical scales are removed to protect proprietary vehicle information.



Model Identification Approach

- Aero-propulsive modeling framework tailored to eVTOL aircraft[1]
- Explanatory variables:
  - Body-axis velocity components (u, v, w) and angular rates (p, q, r)
  - Squared proprotor rotational speeds $(\Omega_1^2, \Omega_2^2, \dots, \Omega_8^2)$ → Linear thrust changes $T = \rho A (\Omega R)^2 C_T$
  - 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 regression[2]
  - Parameter estimation: complex least-squares regression[2]



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

$$X = \overbrace{X_u u + X_w w + X_q q}^{\textbf{State derivatives}} + \overbrace{X_{\delta_{14}}(\delta_1 + \delta_4) + X_{\delta_{23}}(\delta_2 + \delta_3) + X_{\delta_{58}}(\delta_5 + \delta_8) + X_{\delta_{67}}(\delta_6 + \delta_7)}^{\textbf{Control derivatives}} + X_o$$

$$Y = Y_v v + Y_p p + Y_r r + Y_{\Omega^2_{14}}(\Omega_1^2 - \Omega_4^2) + Y_{\Omega^2_{23}}(\Omega_2^2 - \Omega_3^2) + Y_{\Omega^2_{58}}(\Omega_5^2 - \Omega_8^2) + Y_{\Omega^2_{67}}(\Omega_6^2 - \Omega_7^2) + Y_o$$

$$Z = Z_u u + Z_w w + Z_q q + Z_{\Omega^2_{14}}(\Omega_1^2 + \Omega_4^2) + Z_{\Omega^2_{23}}(\Omega_2^2 + \Omega_3^2) + Z_{\Omega^2_{58}}(\Omega_5^2 + \Omega_8^2) + Z_{\Omega^2_{67}}(\Omega_6^2 + \Omega_7^2) + Z_o$$

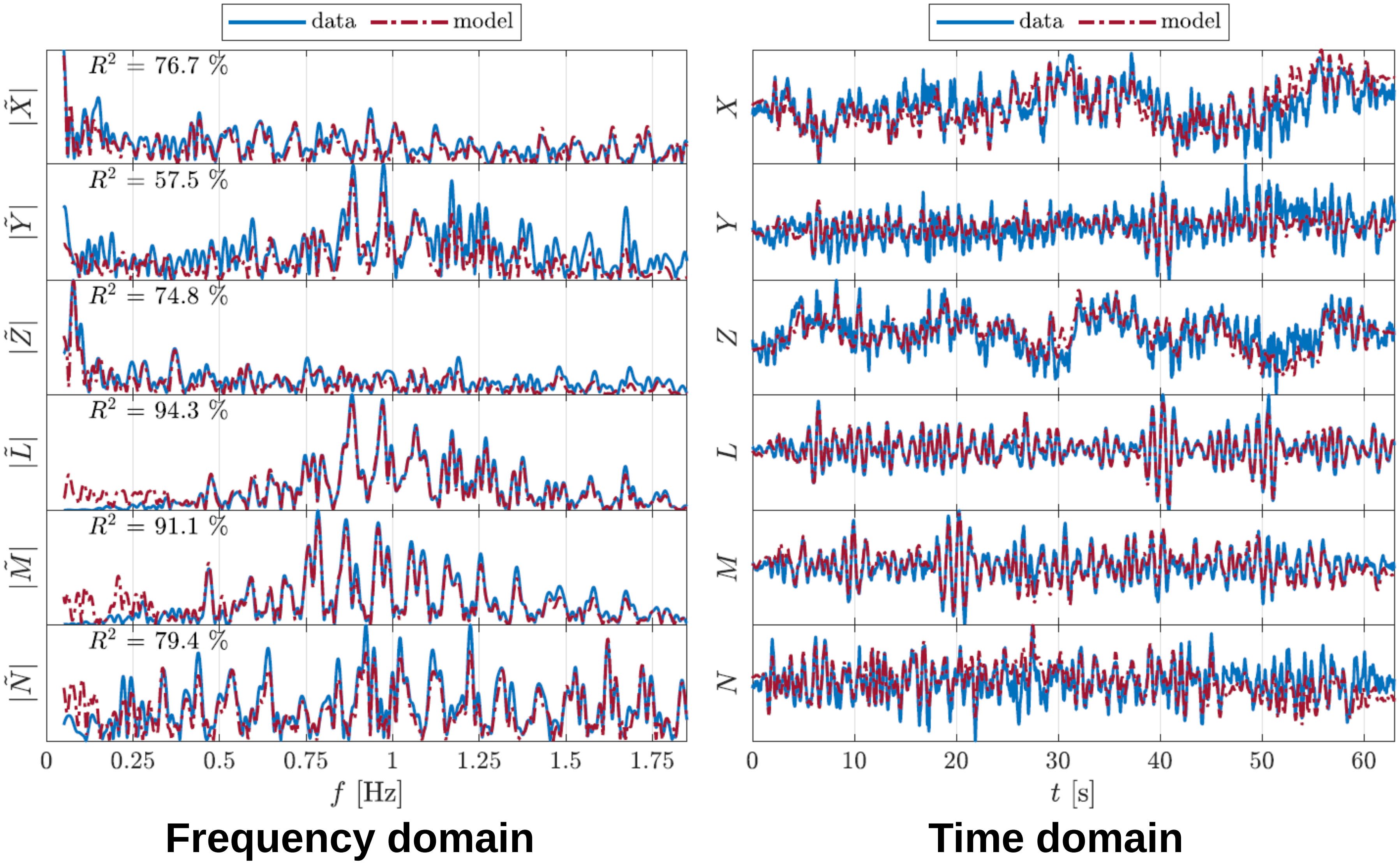
$$L = L_v v + L_p p + L_r r + L_{\Omega^2_{14}}(\Omega_1^2 - \Omega_4^2) + L_{\Omega^2_{23}}(\Omega_2^2 - \Omega_3^2) + L_{\Omega^2_{58}}(\Omega_5^2 - \Omega_8^2) + L_{\Omega^2_{67}}(\Omega_6^2 - \Omega_7^2) + L_o$$

$$M = M_u u + M_w w + M_q q + M_{\Omega^2_{14}}(\Omega_1^2 + \Omega_4^2) + M_{\Omega^2_{23}}(\Omega_2^2 + \Omega_3^2) + M_{\Omega^2_{58}}(\Omega_5^2 + \Omega_8^2) + M_{\Omega^2_{67}}(\Omega_6^2 + \Omega_7^2) + M_o$$

$$N = N_v v + N_p p + N_r r + N_{\delta_{14}}(\delta_1 - \delta_4) + N_{\delta_{23}}(\delta_2 - \delta_3) + N_{\delta_{58}}(\delta_5 - \delta_8) + N_{\delta_{67}}(\delta_6 - \delta_7) + N_o$$

Initial Hover Modeling Results

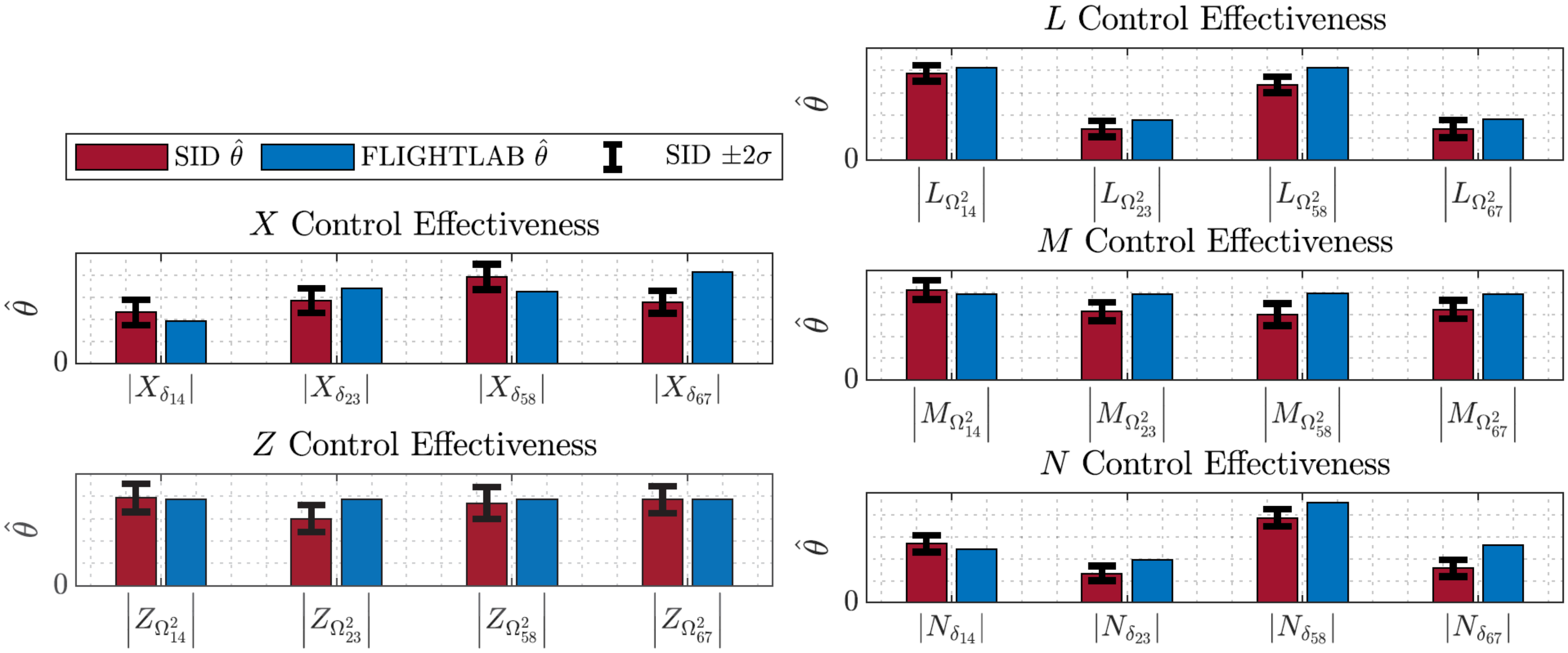
- Complex least-squares regression
- Good model fit for L and M
- Adequate model fit for X, Z, and N
- Lower quality model fit for Y (no direct excitation)



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 speeds[1]
- 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.

Concluding Remarks

- eVTOL aircraft present new system identification challenges
- Orthogonal phase-optimized multisine inputs are valuable for efficient testing and accurate aero-propulsive characterization
- Demonstration of the utility and efficiency of the approach
  - Single 60-second multisine maneuver
  - All control effectiveness parameters identified
  - Assessment and identification of nonlinear model terms, if needed
  - Minimal additional risk posed to the vehicle
- Refinement of test techniques to improve low-speed modeling
- Future testing planned to apply the system identification approach at different parts of the AIBOT 500 flight envelope
- Techniques can be applied for many current and future vehicles

Questions/Discussion

Thank you for attending.

Acknowledgements:

- Support from many AIBOT team members
- First author funding: NASA Aeronautics Research Mission Directorate Transformational Tools and Technologies (TTT) project
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