



Subscale Tiltrotor eVTOL Aircraft Dynamic Modeling, Flight Control Software Development, and Testing Progress

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AIAA HRS Lunch and Learn Technical Seminar

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Contents



- Research motivation/challenges
- RAVEN-SWFT vehicle
- Static wind-tunnel testing
- Flight control system
- Programmed test inputs
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- Flight-test progress
- Flight-test system identification
- Concluding remarks
- Questions



Additional Information



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.
2. Simmons, B. M., and Ackerman, K. A., “System Identification for a Subscale Tiltrotor eVTOL Aircraft from Hover Flight-Test Data,” *AIAA SciTech Forum*, Jan. 2026.

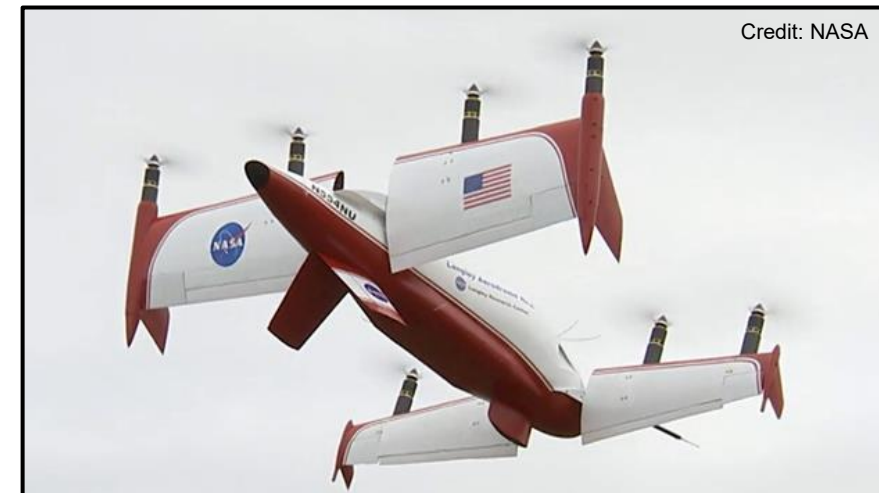
Motivation



- Recent technology advancements enabling practical eVTOL aircraft
- Future Advanced Air Mobility (AAM) transportation system
- eVTOL vehicles are a new class of aircraft with numerous challenges
- New eVTOL aircraft modeling and control strategies are required
- Research aircraft needed for flight dynamics and controls research



NASA GL-10 aircraft

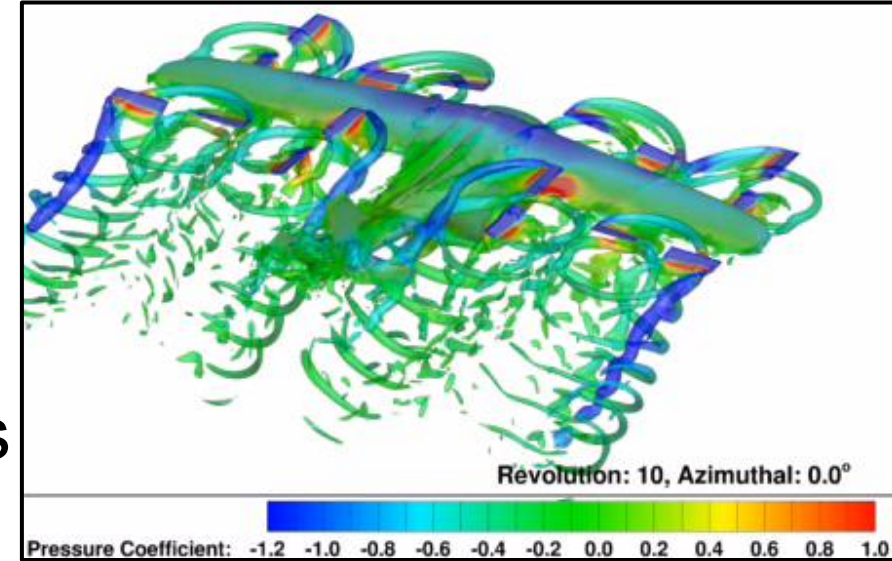


NASA LA-8 aircraft

eVTOL Aircraft Modeling/Control Challenges



- Many control surfaces and propulsors
- Significant propulsion-airframe interactions
- Integrated *aero-propulsive* modeling
- High incidence angle *prop rotor* aerodynamics
- Vehicle instability
- Large flight envelopes to characterize
- Rapidly changing transition aerodynamics
- Characteristics of multiple aircraft types
- Many different configurations



eVTOL aircraft CFD simulation.

Credit: Brian G. Allan (NASA Langley)

**1,180+ known eVTOL
aircraft concepts!**

Reference: <https://evtol.news/aircraft>

eVTOL vehicle configurations exhibit highly complex, nonlinear aerodynamics

Advanced Air Mobility (AAM)



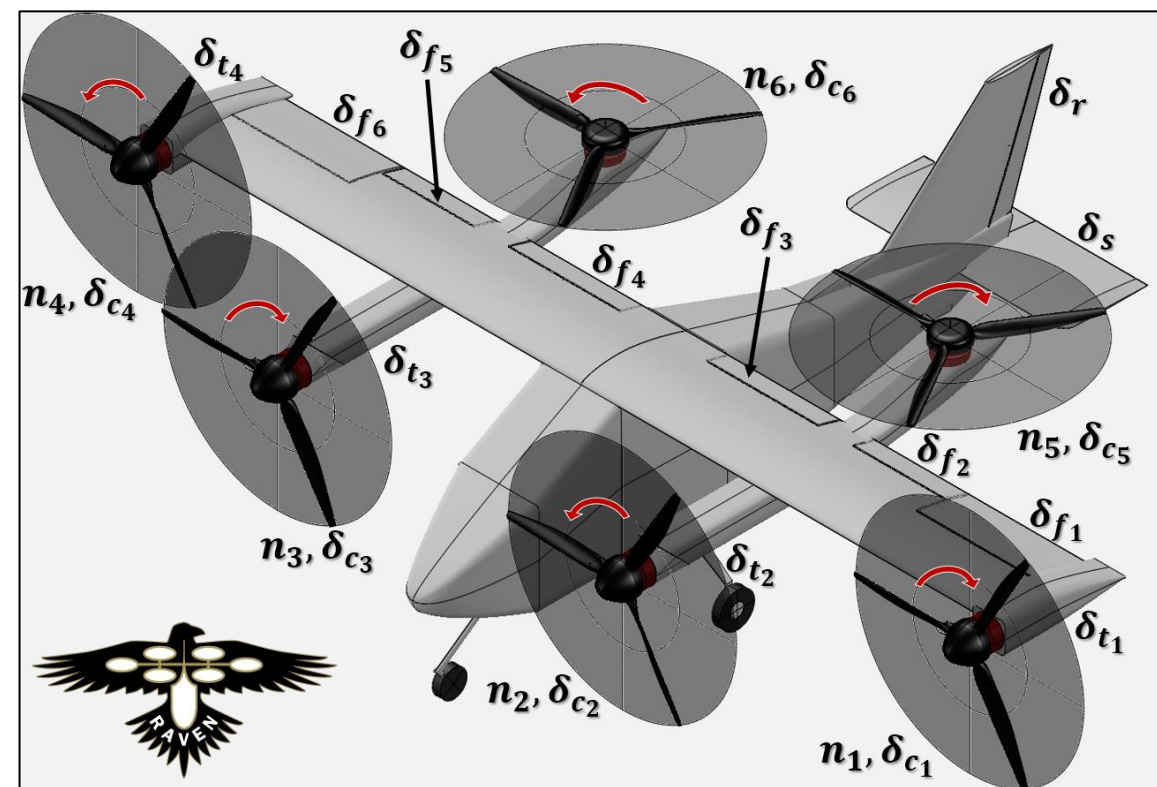
Credit: NASA



NASA RAVEN eVTOL Vehicle



- RAVEN – Research Aircraft for eVTOL Enabling TechNologies^{1,2}
- Tiltrotor eVTOL configuration with six variable-pitch proprotors
- Vehicles at different scales
- 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)
- Created to address eVTOL challenges
- Research platform providing open geometry, data, and methods



RAVEN control effector definitions.

1. <https://www.nasa.gov/raven/>

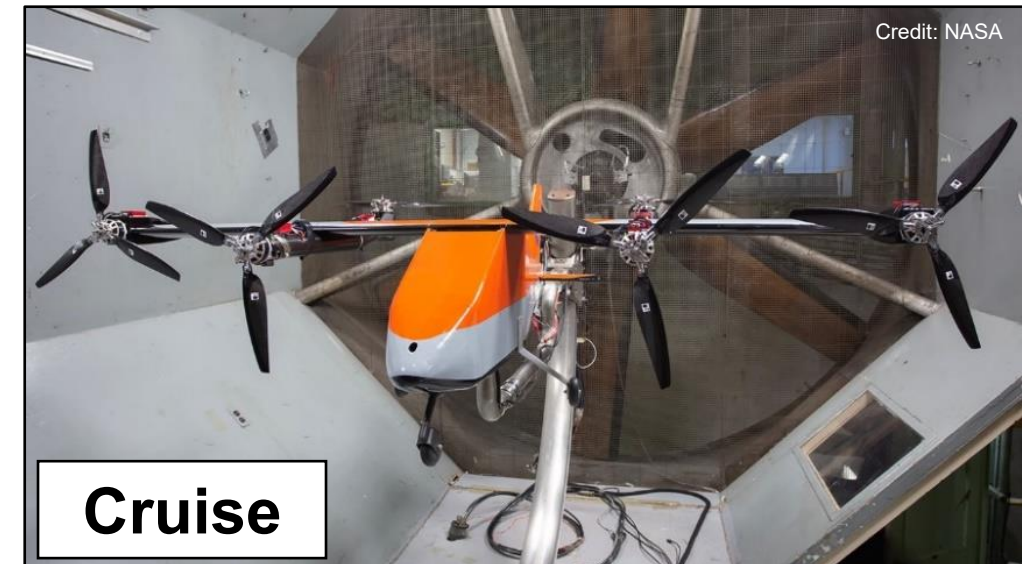
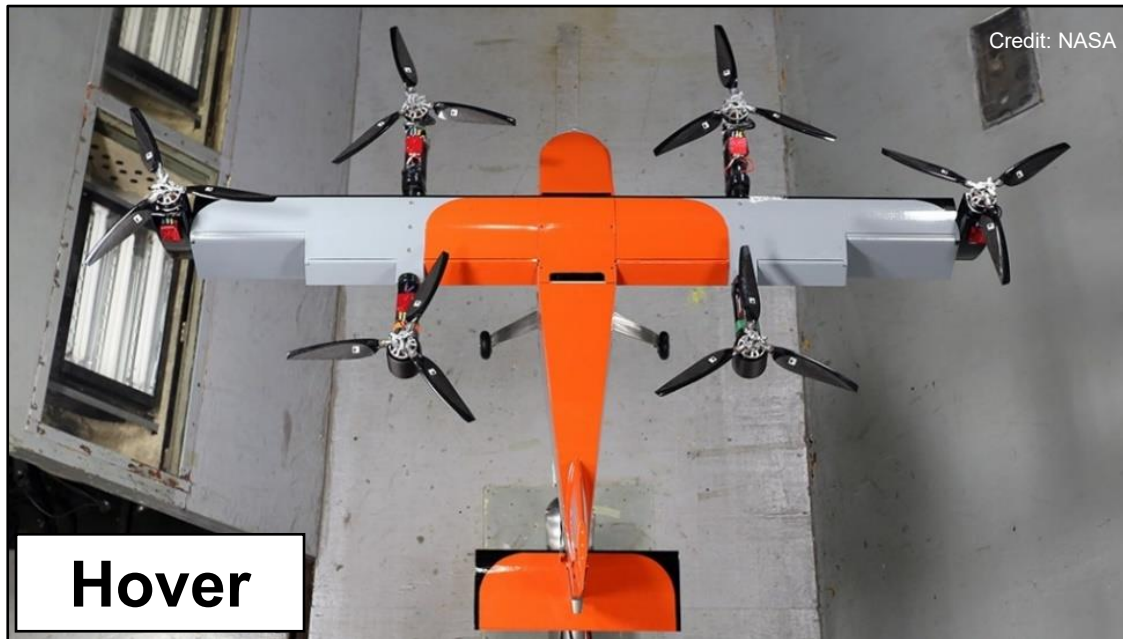
2. German, B. J., Jha, A., Whiteside, S. K. S., and Welstead, J. R., "Overview of the Research Aircraft for eVTOL Enabling techNologies (RAVEN) Activity," *AIAA AVIATION Forum*, June 2023.

RAVEN-SWFT

Research Aircraft for eVTOL Enabling TechNologies (RAVEN)
Subscale Wind-Tunnel and Flight Test (SWFT) Vehicle¹

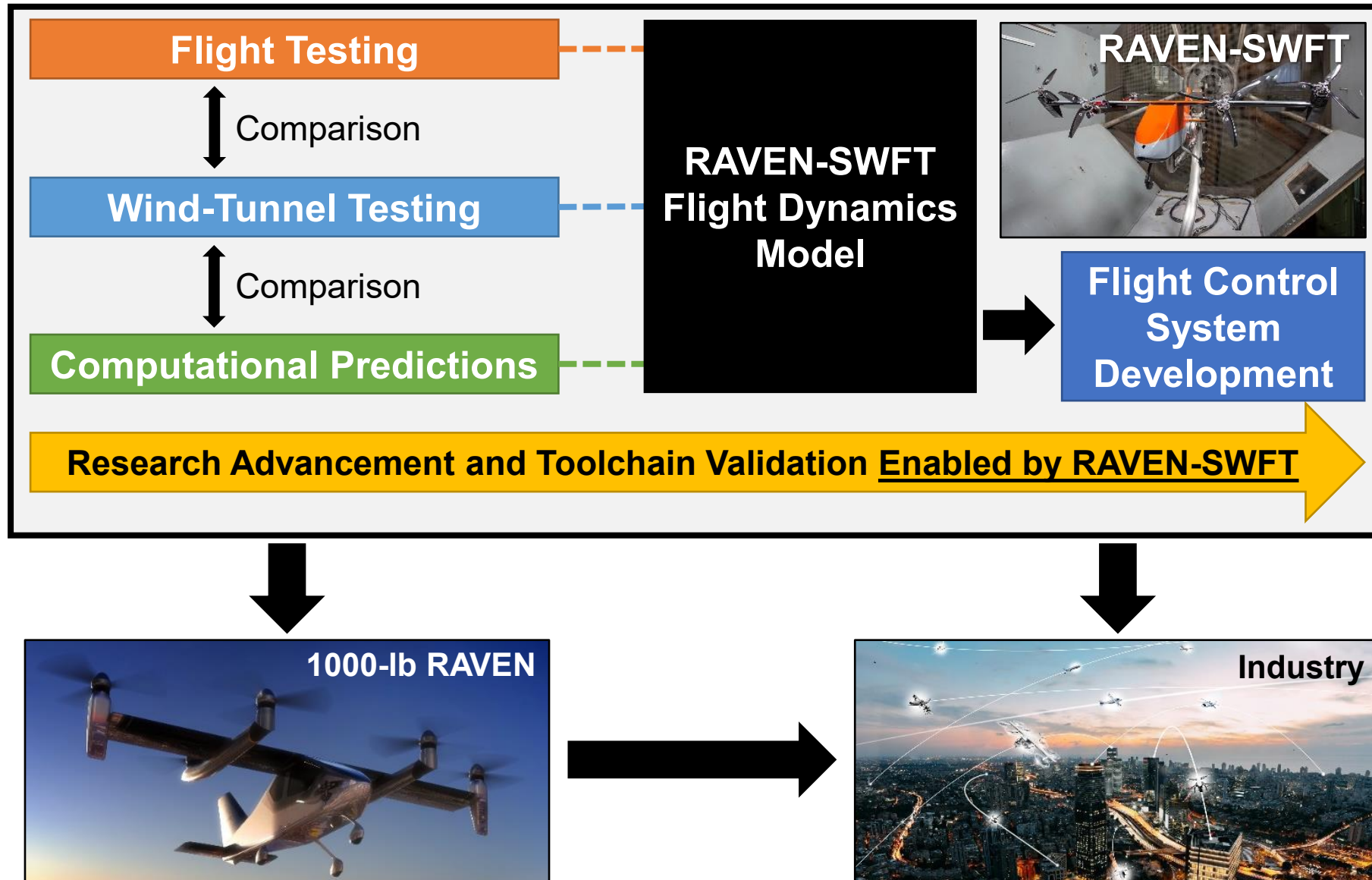


- Wind-tunnel and flight-test research
- Similar scale to NASA LA-8 with expanded utility
- 28.6% scale version of 1000-lb class vehicle
- 38 lb, 5.7 ft wingspan, 19.5 in diam. proprotors
- Built for modeling and controls research



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

RAVEN-SWFT Modeling and Controls



RAVEN-SWFT Wind-Tunnel Testing



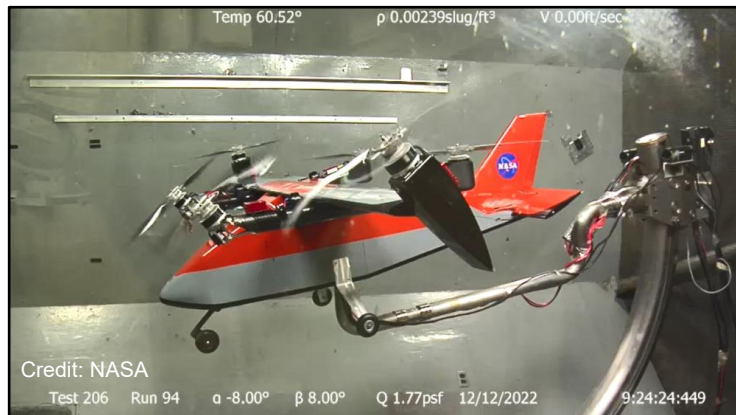
Langley 12-Foot Low-Speed Tunnel

- Isolated proprotor testing¹
- Static full-airframe testing²
- Dynamic free-motion testing³



Credit: NASA

Proprotor



Powered-airframe

RAVEN-SWFT wind tunnel tests.

1. Simmons, B. M., "Efficient Variable-Pitch Propeller Aerodynamic Model Development for Vectored-Thrust eVTOL Aircraft," *AIAA AVIATION 2022 Forum*, June 2022.
2. Simmons, B. M., and Busan, R. C., "Statistical Wind-Tunnel Experimentation Advancements for eVTOL Aircraft Aero-Propulsive Model Development," *AIAA SciTech 2024 Forum*, January 2024.
3. 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*, Vol. 63, No. 2, 2026, pp. 465–479.

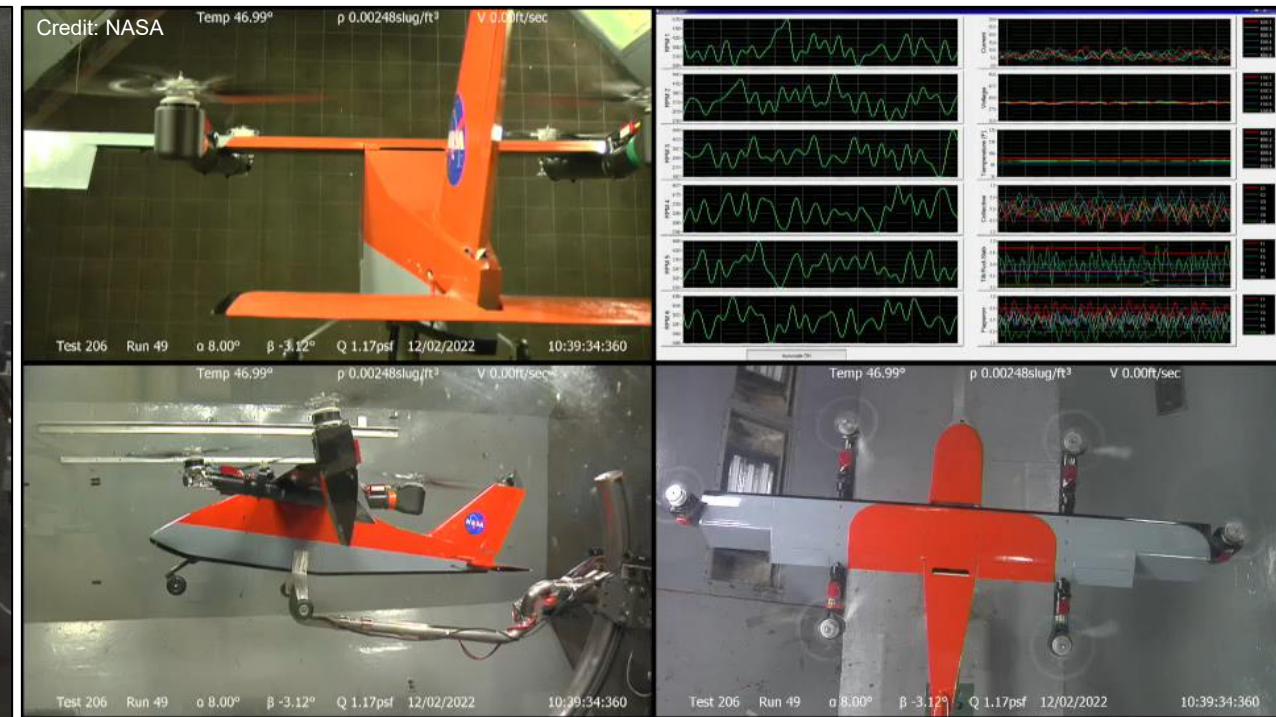
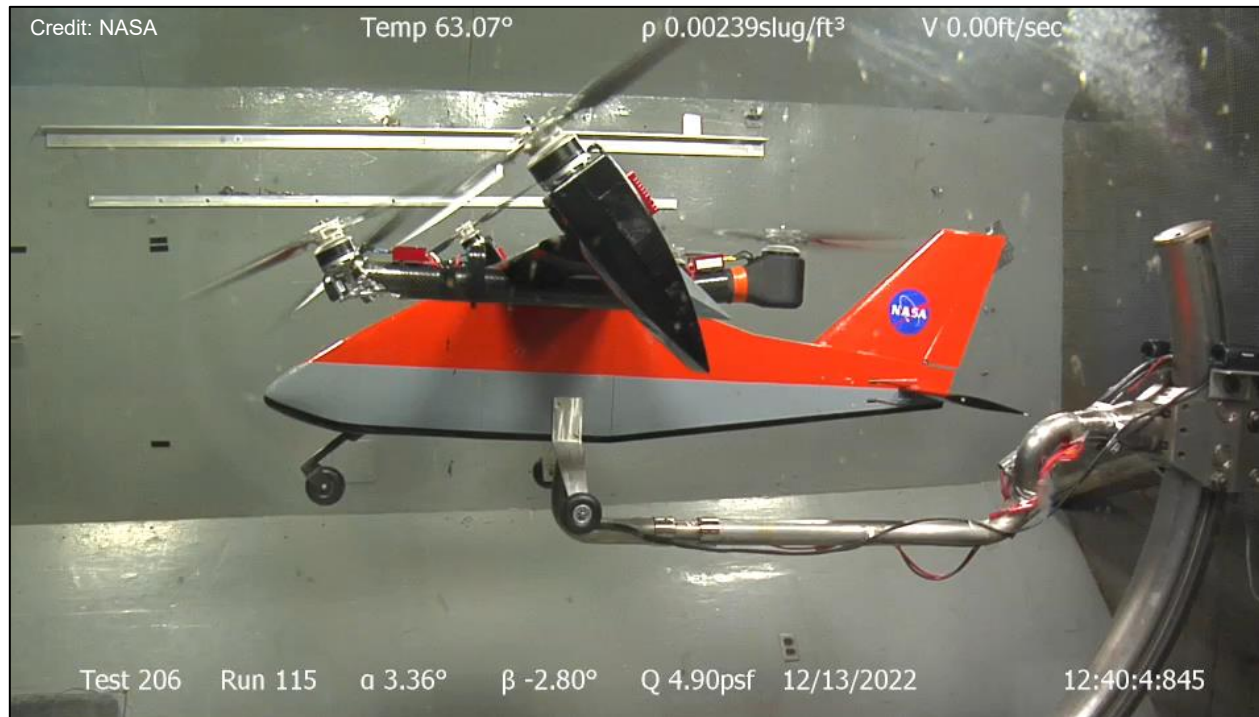
Advanced Test Techniques

- Design of experiments (DOE)
- Response surface methods (RSM)
- Programmed test inputs (PTI)
- Three degree-of-freedom (3DOF)

Purpose

- Flight simulation development
- Flight control system design
- Validation of prediction tools
- Data/models that can be published

RAVEN-SWFT Powered-Airframe Testing



Static DOE/RSM testing (x20 speed).

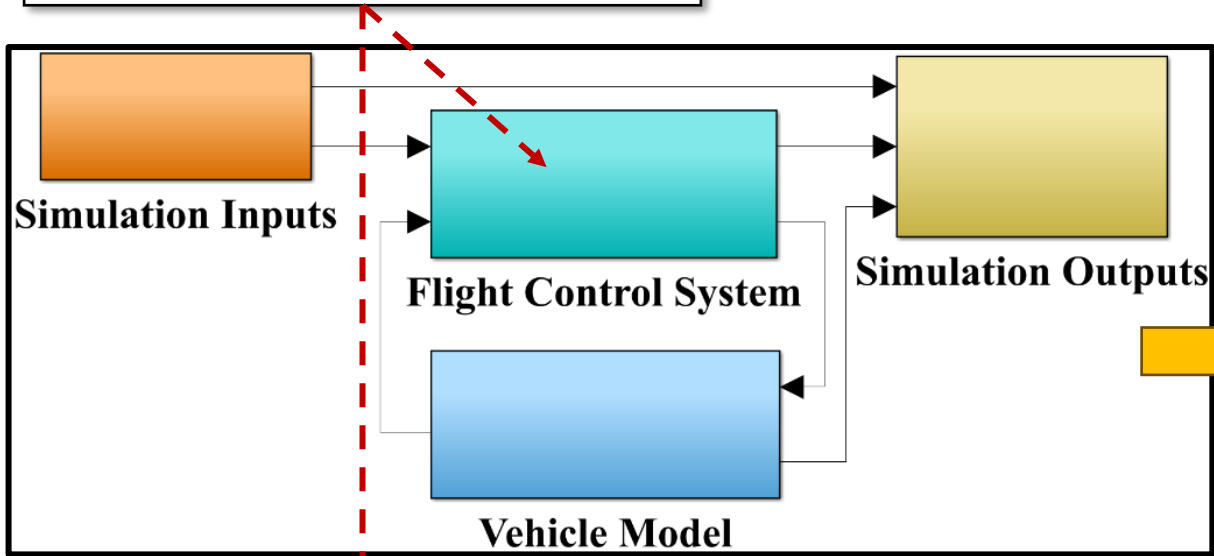
Hybrid PTI/DOE/RSM testing (x1 speed).

1. Simmons, B. M., "Evaluation of Response Surface Experiment Designs for Distributed Propulsion Aircraft Aero-Propulsive Modeling," *AIAA SciTech Forum*, January 2023.
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 2024 Forum*, January 2024.

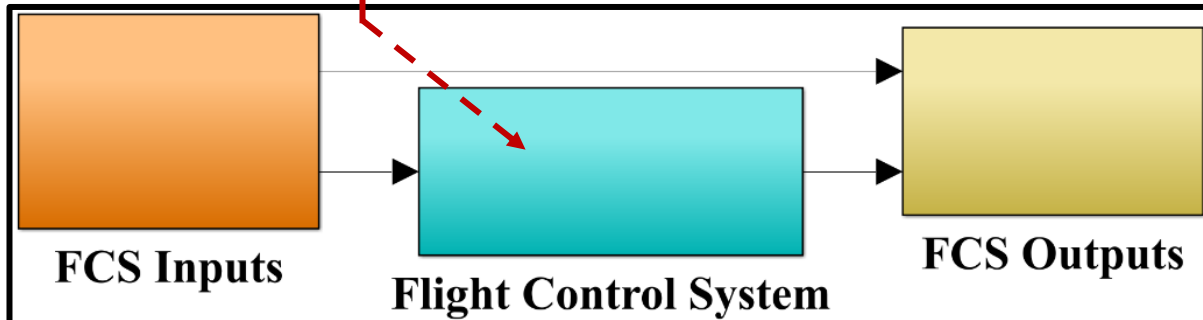
Simulation and Control System Development¹



Same Control Laws



Top-level of flight dynamics simulation.



Top-level of integrated flight control system.



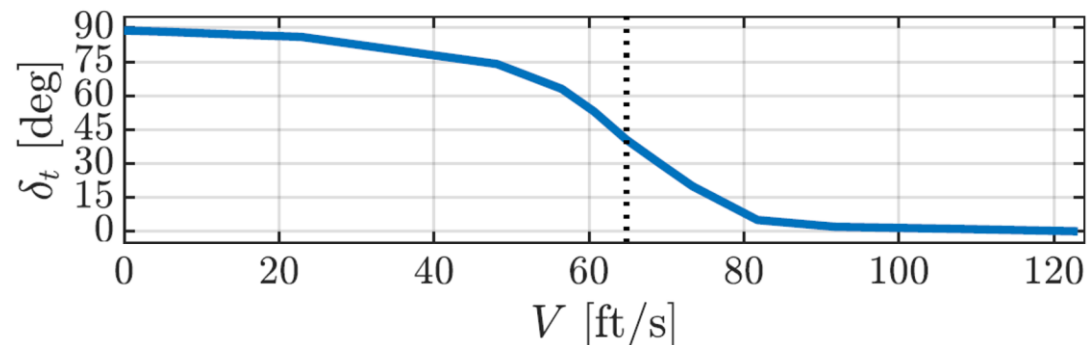
RAVEN-SWFT piloted simulation in X-Plane.

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.

Unified Flight Control Algorithm Overview



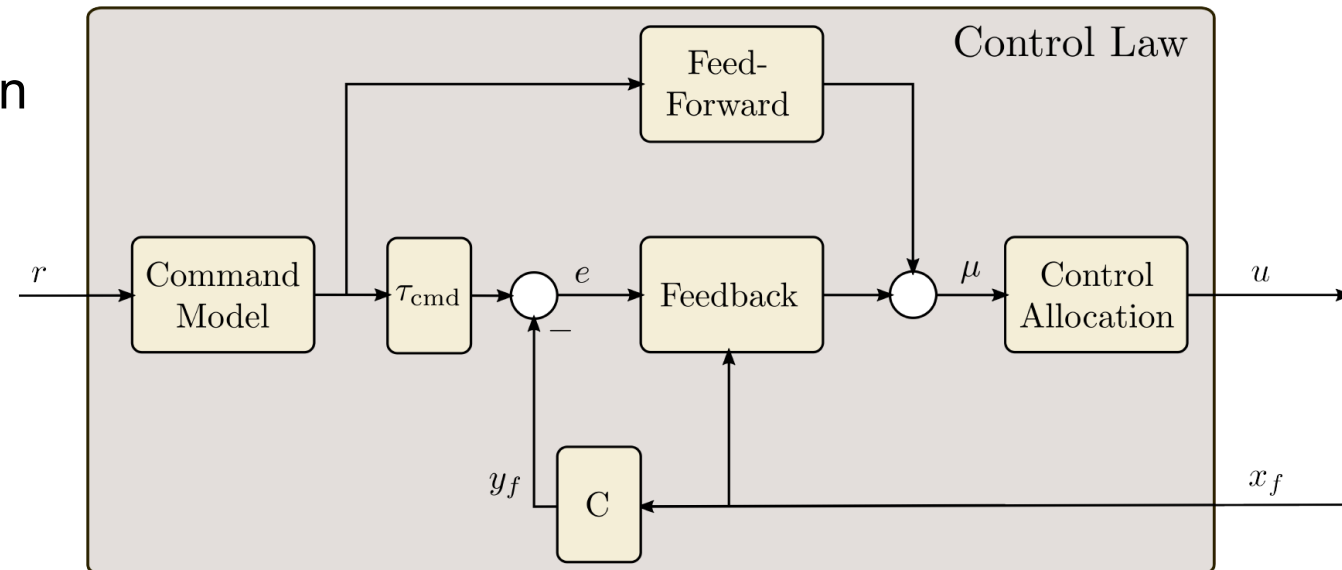
- Nested-loop architecture
 - Attitude-tracking inner loop
 - Velocity-tracking outer loop
- Model-based control design approach
 - Performance and robustness requirements
 - Linearization of simulation at trim conditions
 - Linear quadratic integral (LQI) model-following control framework with feedforward element
 - Weighted pseudo-inverse control allocation
 - Scheduling with dynamic pressure
 - Lead: Kasey Ackerman, NASA Langley



Nacelle tilt angle trim settings.

Pilot command variables

Pilot Interface	Command Type	Unified Velocity (FCS Mode 2)
Right Stick ($\leftrightarrow$)	Lateral	Lateral Velocity ($\bar{v}$)
Right Stick ($\updownarrow$)	Longitudinal	Forward Velocity ($\Delta \bar{u}$)
Left Stick ($\leftrightarrow$)	Directional	Yaw Rate ($\dot{\psi}$)
Left Stick ($\updownarrow$)	Vertical	Vertical Velocity ($\bar{w}$)
Left Slider	Transition	Forward Velocity ($\bar{u}$)

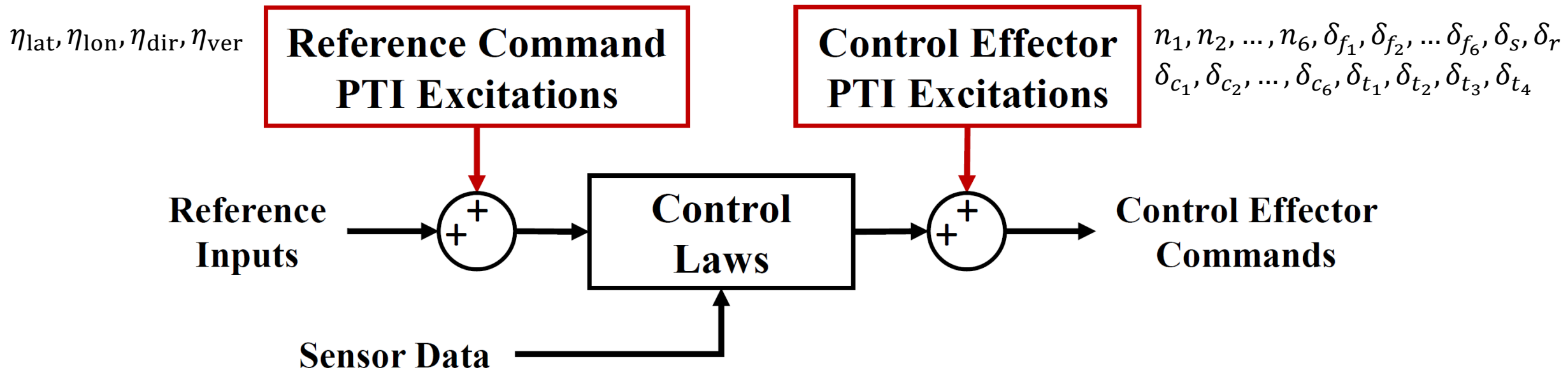


Inner-/outer-loop control law structure schematic.

Programmed Test Input (PTI) Injection



- **Objective:** generate informative data for model identification
- Multiple-input excitation required for efficient testing → multisines
- Several PTI types integrated into flight control software
- Includes both reference command and control effector PTI excitations



Programmed test input injections relative to the control laws.

RAVEN-SWFT Multisine Input Design



- Orthogonal phase-optimized multisine inputs^{1,2}
- 28 unique multisine PTI excitation signals
- Simultaneous excitation in all axes

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

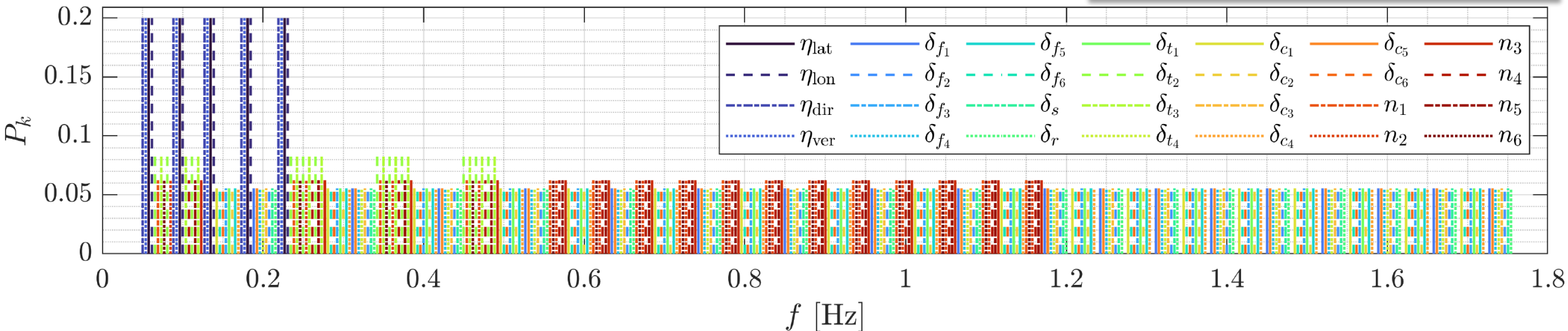
$u_j(t)$ – j th multisine signal

A – signal amplitude

P_k – k th power fraction

T – fundamental period

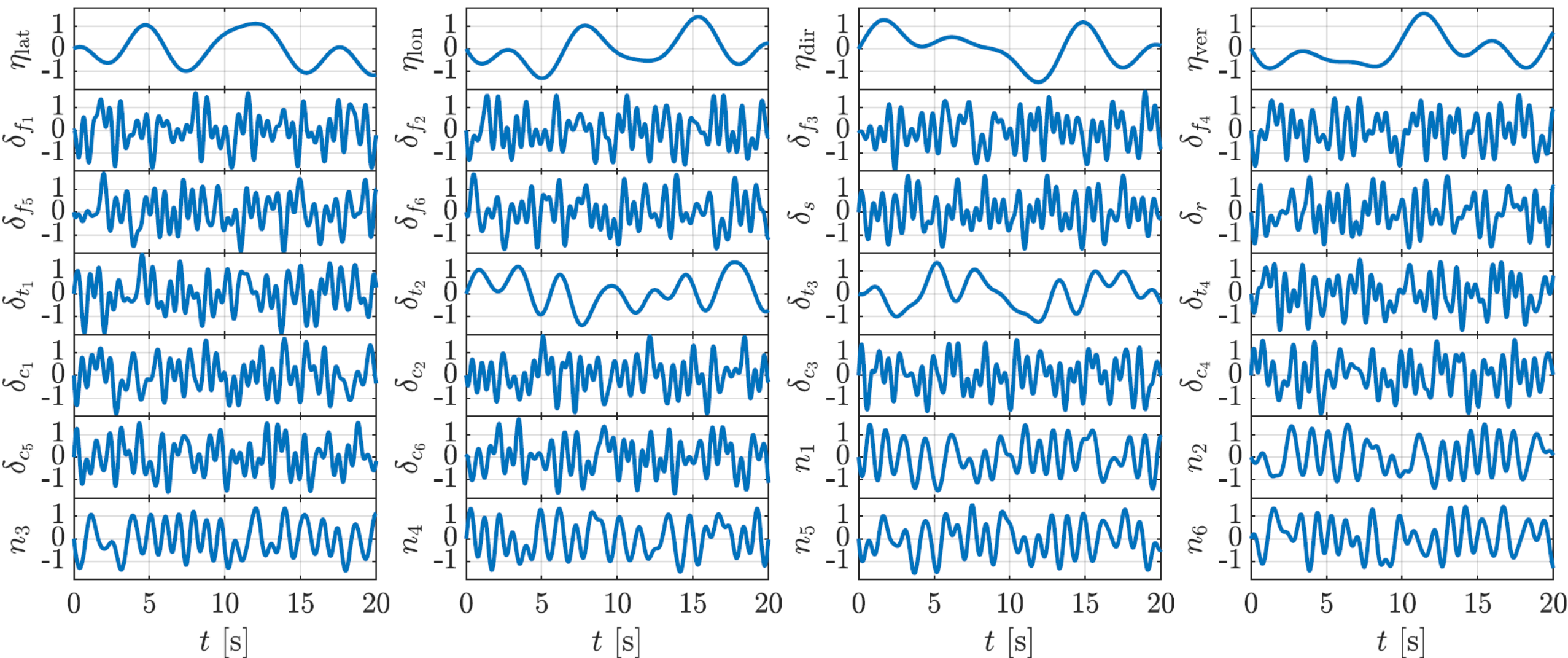
ϕ_k – k th phase angle



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.

Flight Control Software Integration



- **Goal:** streamlined process to deploy flight control algorithms developed in MATLAB/Simulink[®] onto the RAVEN-SWFT vehicle
- Refinement using low-cost, off-the-shelf, surrogate vehicles^{1,2,3}
- MathWorks[®] UAV Toolbox and Support Package for PX4 Autopilots
- Pixhawk flight computer running custom PX4 firmware
 - PX4 outer- and inner-loop control laws are replaced with custom control laws
 - Other support functionality retained (estimation algorithm, safety logic, etc.)
- Control software updates built/deployed to the vehicle in <5 minutes

1. Asper, G. D., and Simmons, B. M., "Rapid Flight Control Law Deployment and Testing Framework for Subscale VTOL Aircraft," NASA TM–20220011570, September 2022.
2. Asper, G. D., Simmons, B. M., Axten, R. M., Ackerman, K. A., and Corrigan, P. E., "Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT): Development, Integration, and Experimentation," NASA TM–20240000223, March 2024.
3. Comer, A. M., Simmons, B. M., and Asper, G. D., "Design, Simulation, and Flight Testing of a Multi-Purpose VTOL Flight Control System," NASA TM–20250000954, September 2025.

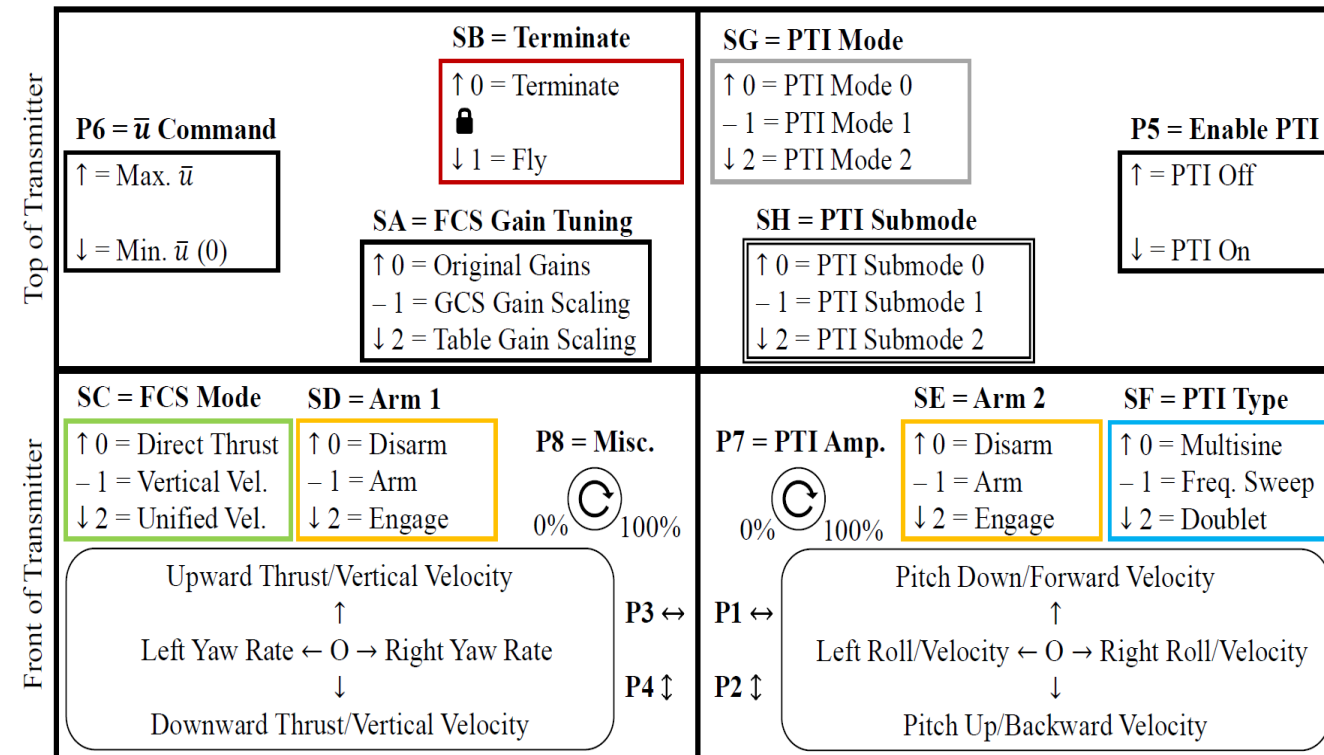
Additional Software Development Aspects



- Flight dynamics simulation subsystems
- Control system integration subsystems
- Control law design/tuning approach
- Trim strategy
- Flight control modes
- Takeoff and landing sequence
- RC transmitter commands
- Ground control station commands
- Sensors and data acquisition
- Software assurance
- Airworthiness considerations

Additional details:

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.



RAVEN-SWFT RC transmitter programming.

Three Degree-of-Freedom (3DOF) Testing



- New 3DOF rig designed and built in-house¹
 - Free rotational motion
 - Aerodynamic damping characterization
 - Flight control algorithm evaluation
- Custom RAVEN-SWFT 3DOF control system
 - Model-based control design approach
 - Tracks commanded attitude angles
 - Scheduling with dynamic pressure
 - Programmed test input (PTI) injection capability
 - Control algorithm deployed to an onboard Pixhawk
- Wind-tunnel testing approach
 - Dynamic pressure set using the wind-tunnel system
 - RC transmitter and GCS computer command vehicle
 - Onboard instrumentation – no balance
 - Similar hardware and software used for flight testing

1. Credit: Ron Busan, Vehicle Dynamics and Control Branch, NASA Langley



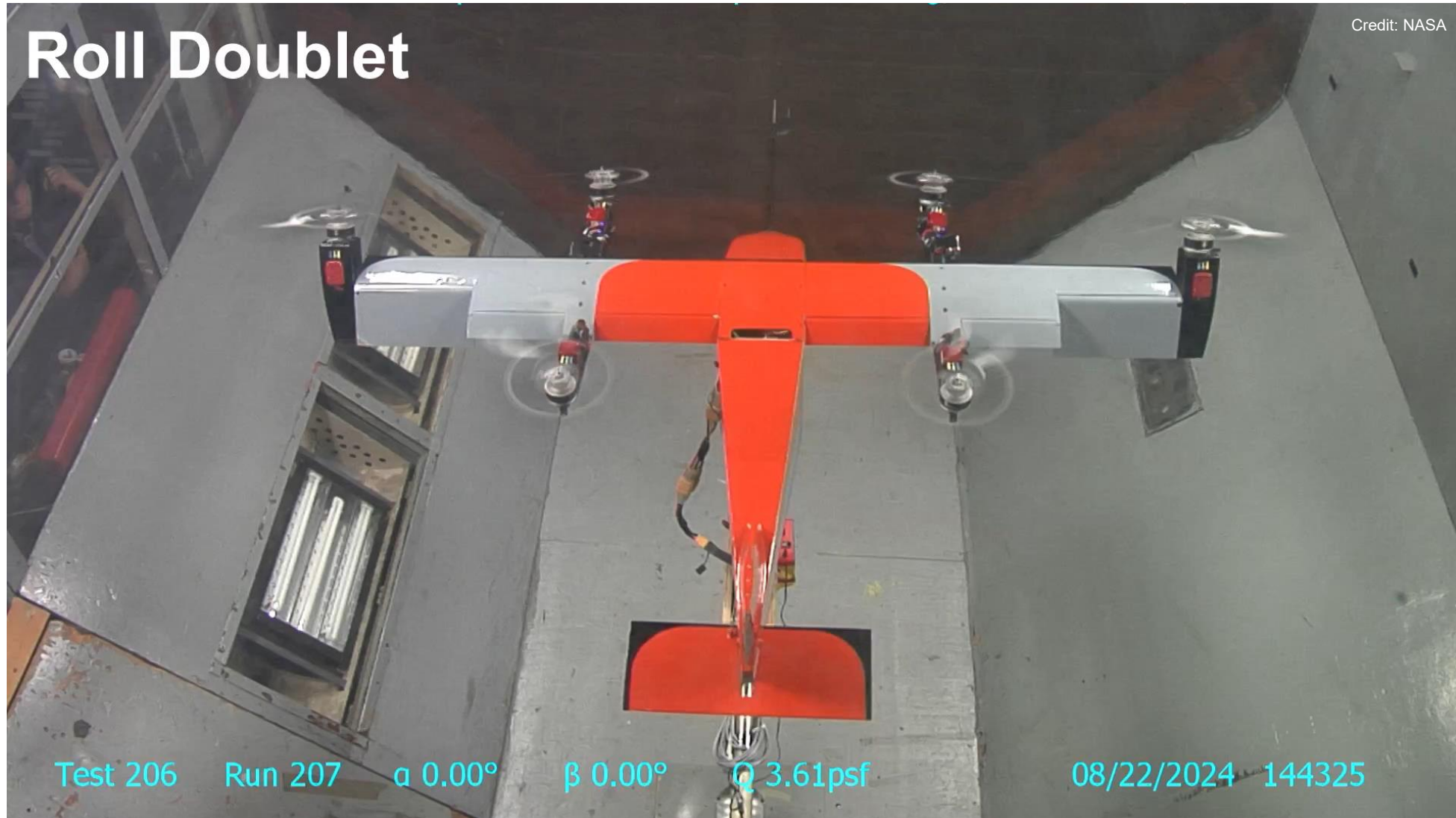
RAVEN-SWFT mounted on a 3DOF rig.

RAVEN-SWFT 3DOF Test Video



Roll Doublet

Credit: NASA



Test 206

Run 207

α 0.00°

β 0.00°

Q 3.61psf

08/22/2024

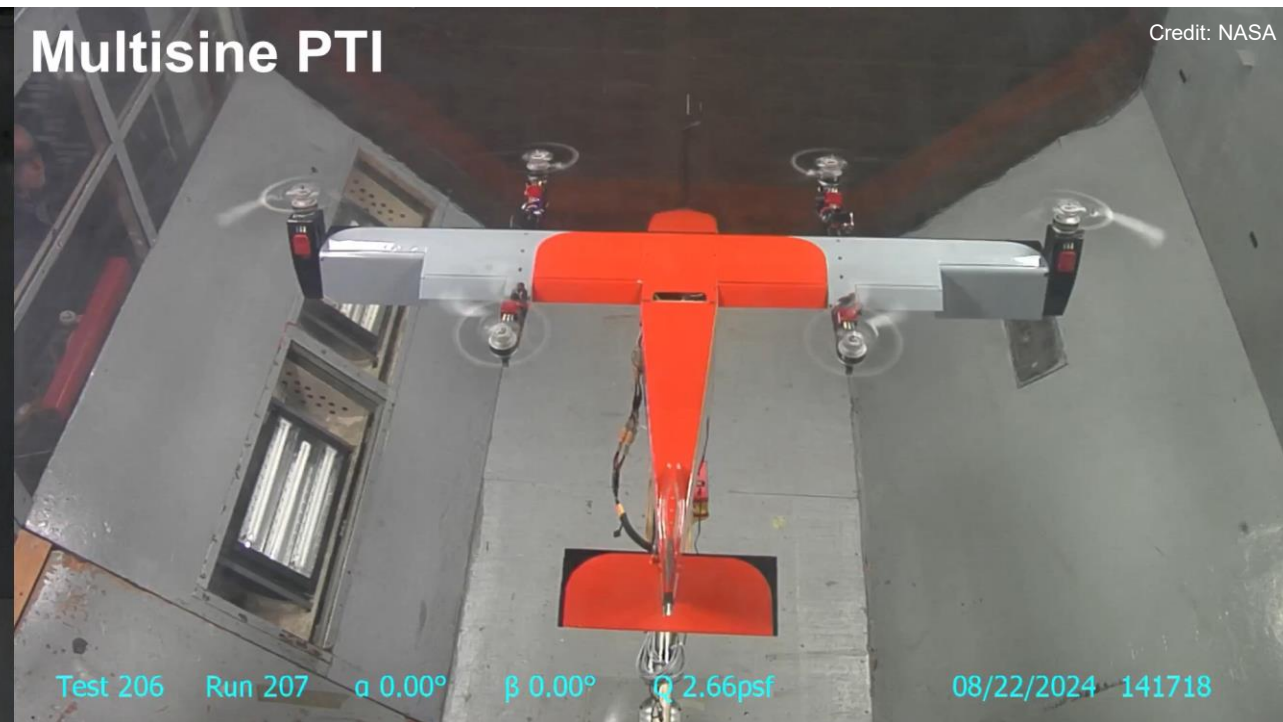
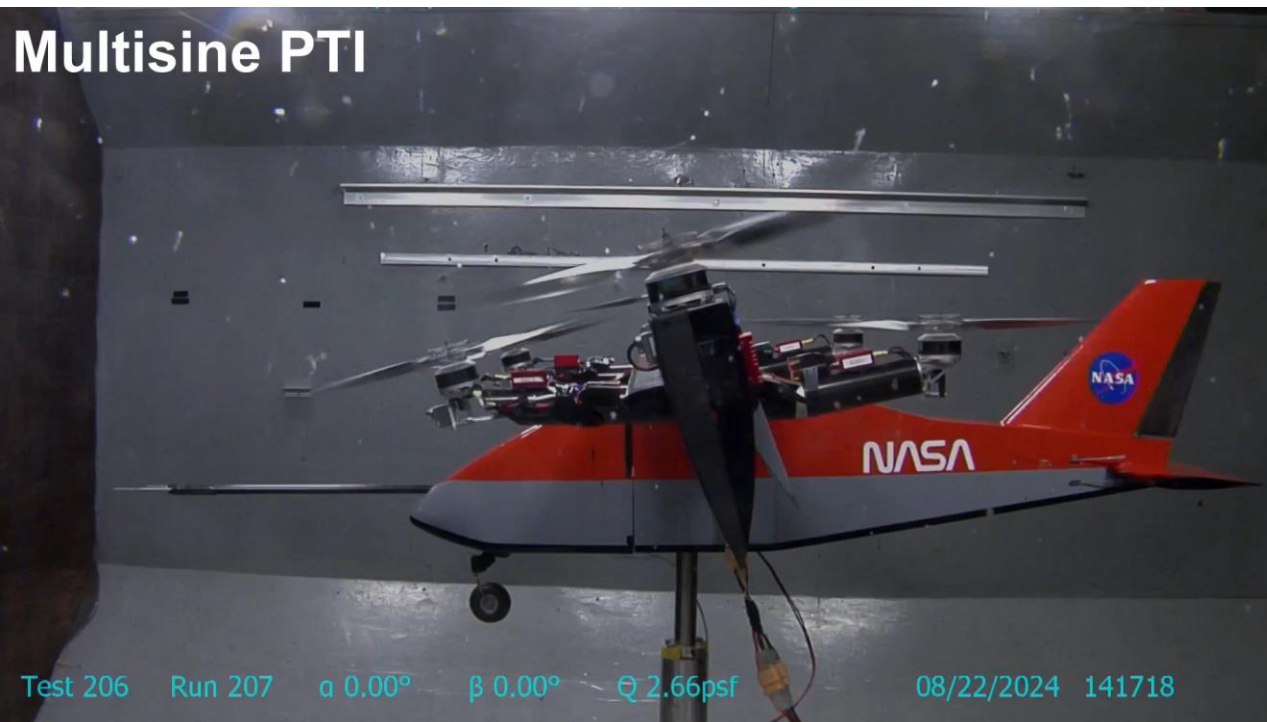
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Attitude step commands at $\bar{q} = 3.79$ lbf/ft².

RAVEN-SWFT 3DOF Multisine Maneuver



- PTIs are injected into the attitude and control effector commands
- All aircraft dynamics of interest are simultaneously excited
- Flight controller stabilizes the vehicle and tracks the commanded attitude



Multisine PTI excitations at $\bar{q} = 2.75 \text{ lbf/ft}^2$.

1. 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*, Vol. 63, No. 2, 2026, pp. 465–479.

RAVEN-SWFT Tethered Flight Testing



- NASA Langley CERTAIN Range
- Tether suspended above the vertipad using a large articulating boom lift
- Verification of hover flight controller



RAVEN-SWFT Tethered Flight Testing



Credit: NASA

RAVEN-SWFT Free Flight Testing



- Ongoing flight-test envelope expansion at NASA Langley CERTAIN Range
- Transition unified flight control algorithm verification and refinement
- System identification research and aero-propulsive model validation



Takeoff, partial transition, and landing

Reference command doublet PTIs

RAVEN-SWFT low-speed flight testing.

Hover System Identification Research¹



- Demonstration and refinement of system identification approach for eVTOL aircraft
- Multiple maneuvers were studied – two maneuver types 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 System Identification Findings¹



- Orthogonal phase-optimized multisines are essential for efficient testing
- PTI injections both before and after the control laws are important
- Accurate hover models identified with short flight-test maneuver times

CE Multisine PTI

Credit: NASA



RC+CE Multisine PTI

Credit: NASA



See the paper for
additional details

Hover CE multisine maneuver.

Hover RC+CE multisine maneuver.

Concluding Remarks



- eVTOL aircraft present new modeling and flight control challenges
- RAVEN-SWFT developed to advance modeling and controls research
- Custom research flight control software development and refinement
- Extensive wind-tunnel testing and ongoing flight testing
- Current focus on RAVEN-SWFT transition flight envelope expansion
- Techniques can be applied for many current and future vehicles



Next Steps



- Flight control algorithm and system ID testing 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 and control techniques

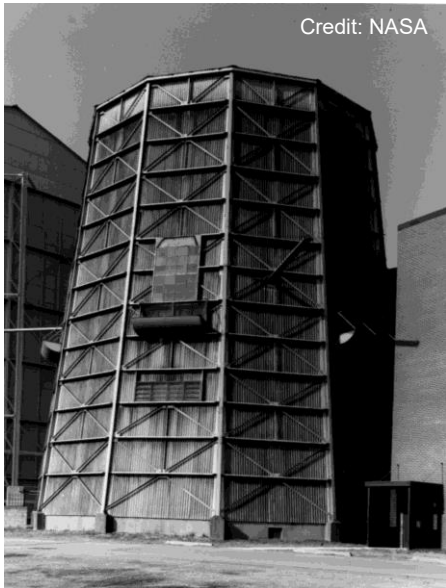


NASA RAVEN vehicle renderings.

Coming Soon: NASA Langley FDRF

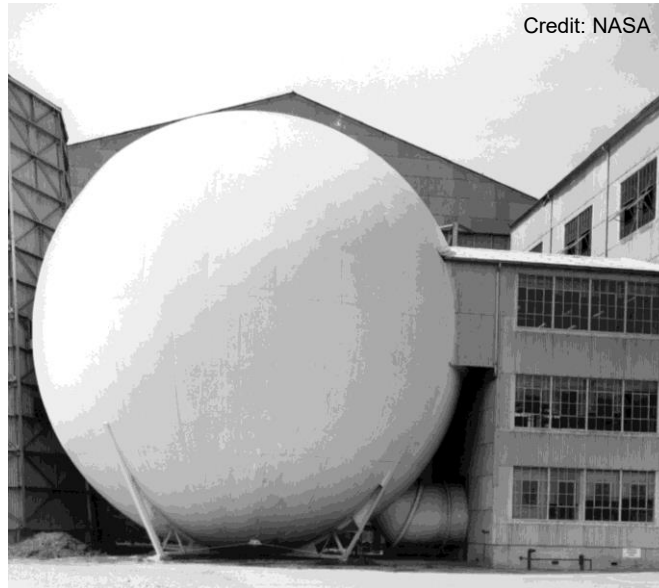


- Flight Dynamics Research Facility (FDRF)
- Combining/expanding capabilities of:
 - 20-Foot Vertical Spin Tunnel (VST)
 - 12-Foot Low-Speed Tunnel (LST)
- Scheduled to open in 2026
- Similar vehicles and research flexibility



20-Foot VST

Simmons, NASA Langley



12-Foot LST

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FDRF photograph (March 24, 2026)

Fremaux, C. M., Simmons, B. M., Owens, D. B., Vicroy, D. D., Storch, D. B., “Development and Capabilities of the NASA Flight Dynamics Research Facility,” *AIAA SciTech Forum*, Jan. 2025.

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- **Wind-tunnel testing:** Ron Busan, Stephen Farrell, Earl Harris, Rick Thorpe, Clinton Duncan, Wes O'Neal, Lee Pollard, and Vincent Spada
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- **Project leadership:** Siena Whiteside, Jason Welstead, Jake Schaefer, Steve Riddick, and Mike Acheson

Questions/Discussion

Thank you for attending.

References:

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. <https://doi.org/10.4050/F-0081-2025-161>.
2. Simmons, B. M., and Ackerman, K. A., “System Identification for a Subscale Tiltrotor eVTOL Aircraft from Hover Flight-Test Data,” *AIAA SciTech Forum*, Jan. 2026, <https://doi.org/10.2514/6.2026-2088>.