Aero-Propulsive Modeling for eVTOL Aircraft Using Experimental Data

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Flight Dynamics Branch

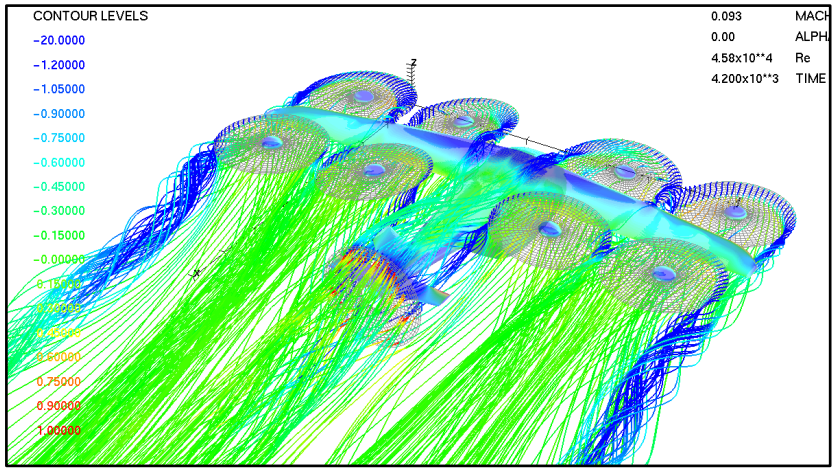
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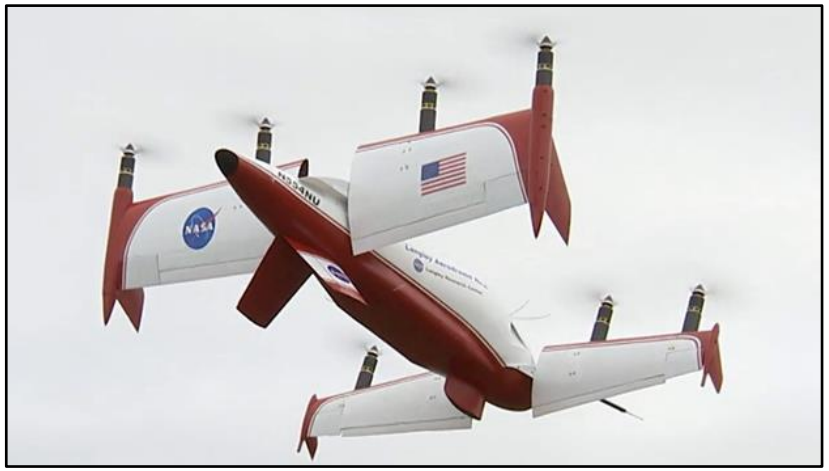
- Research motivation, background, and challenges
- Overview of eVTOL aircraft modeling approach
- Wind-tunnel, CFD, and flight-test applications
- Concluding remarks
- Questions/discussion



Lift+Cruise CFD simulation.



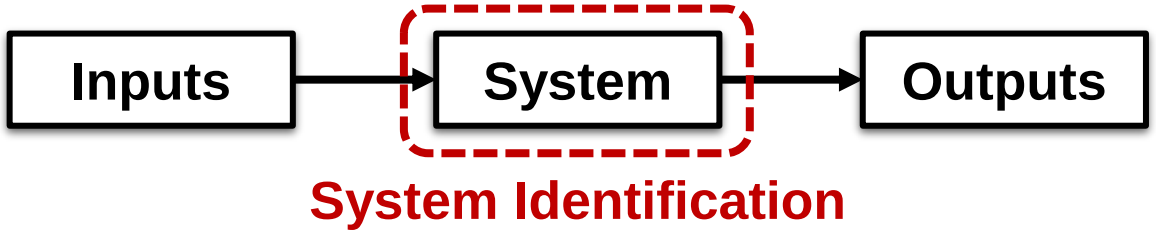
RAVEN-SWFT wind-tunnel test.



LA-8 flight test.

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





LA-8 wind-tunnel testing.



LA-8 flight testing.

Research Motivation

- Recent technology advancements enabling practical eVTOL aircraft
- Future Advanced Air Mobility (AAM) transportation system
- Flight simulations driven by high-fidelity aero-propulsive models are needed for technology development → experimental data
- eVTOL vehicles are a new class of aircraft with numerous challenges
- Conventional methods fail to efficiently characterize eVTOL aircraft
- New eVTOL aircraft testing and modeling strategies are required

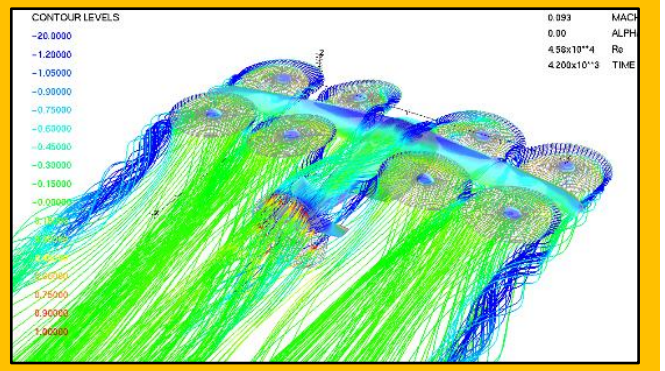
Objective: Develop aero-propulsive characterization methods for eVTOL vehicles enabling flight dynamics simulation development

NASA LaRC eVTOL Modeling/Controls Research

GL-10



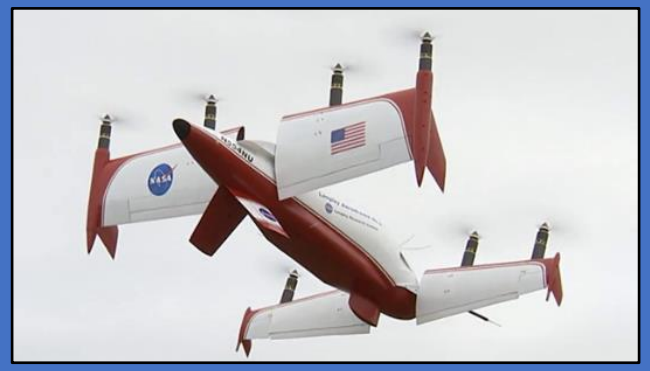


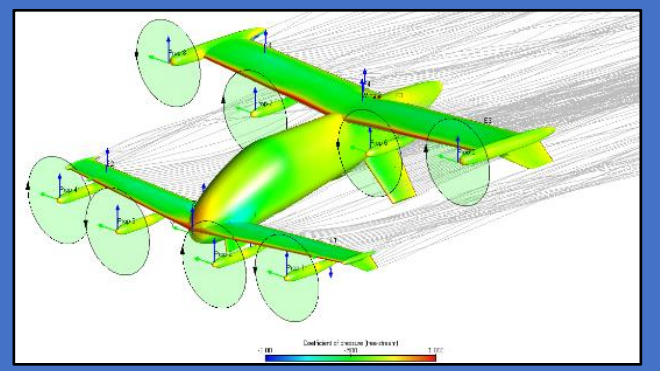


Lift+ Cruise

LA-8

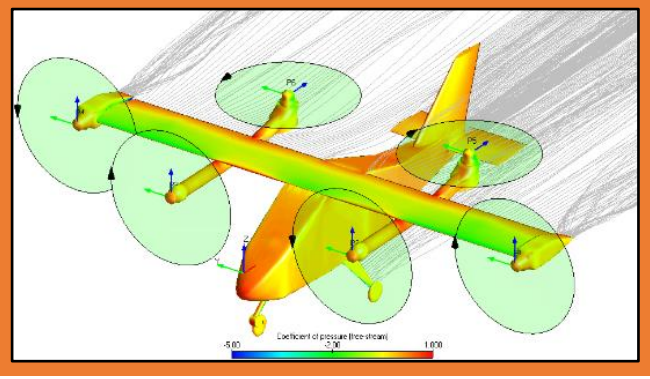


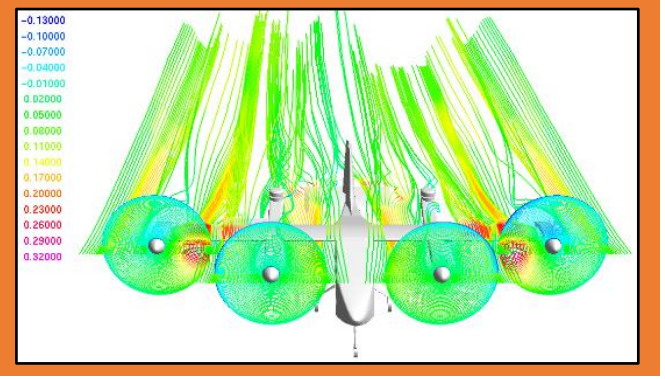




RAVEN

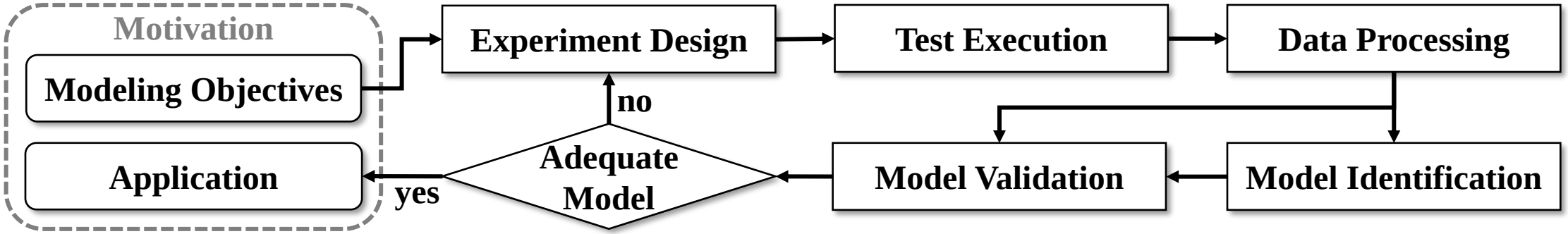






Modeling From Experimental Data

General process for aircraft system identification



Computational or Wind-Tunnel Testing

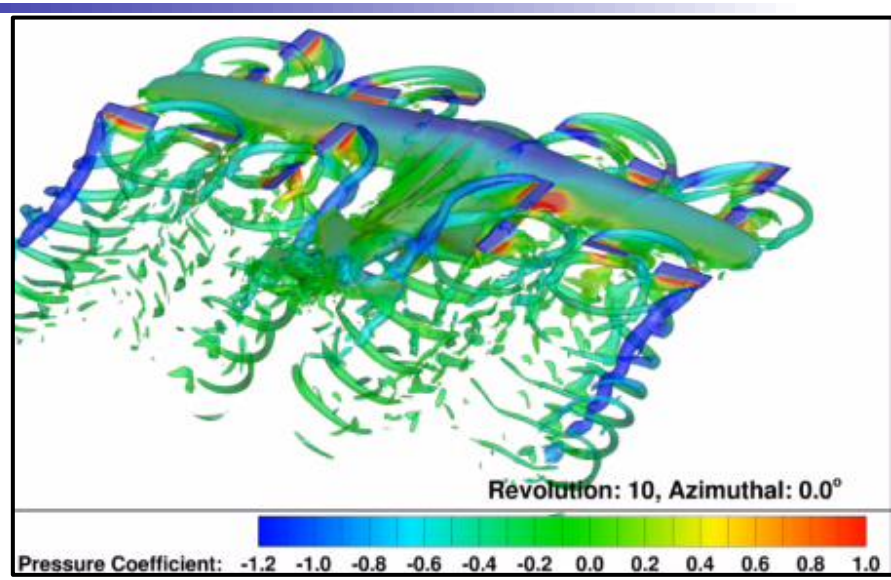
- State and control variables are directly specified in the experiment design
- Applied forces (X, Y, Z) and moments (L, M, N) are directly measured
- Time-averaged and/or time history data
- **Benefits:** controlled environment, accurate sensors, lower risk
- **Issues:** environmental and geometric differences, unrealistic conditions

Flight Testing

- Control variables are directly specified and designed to traverse the state variable space
- Forces and moments are inferred from other measurements and known aircraft properties
- Continuous time history data
- **Benefits:** closest to operational reality, modeling from the actual vehicle, most accurate models
- **Issues:** noisy sensors, atmospheric disturbances, risk

eVTOL Aircraft Modeling Challenges

- Many control surfaces and propulsors
- Significant propulsion-airframe interactions
- Integrated *aero-propulsive* modeling
- High incidence angle *proprotor* 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)

900+ known eVTOL aircraft concepts!
Reference: https://evtol.news/aircraft

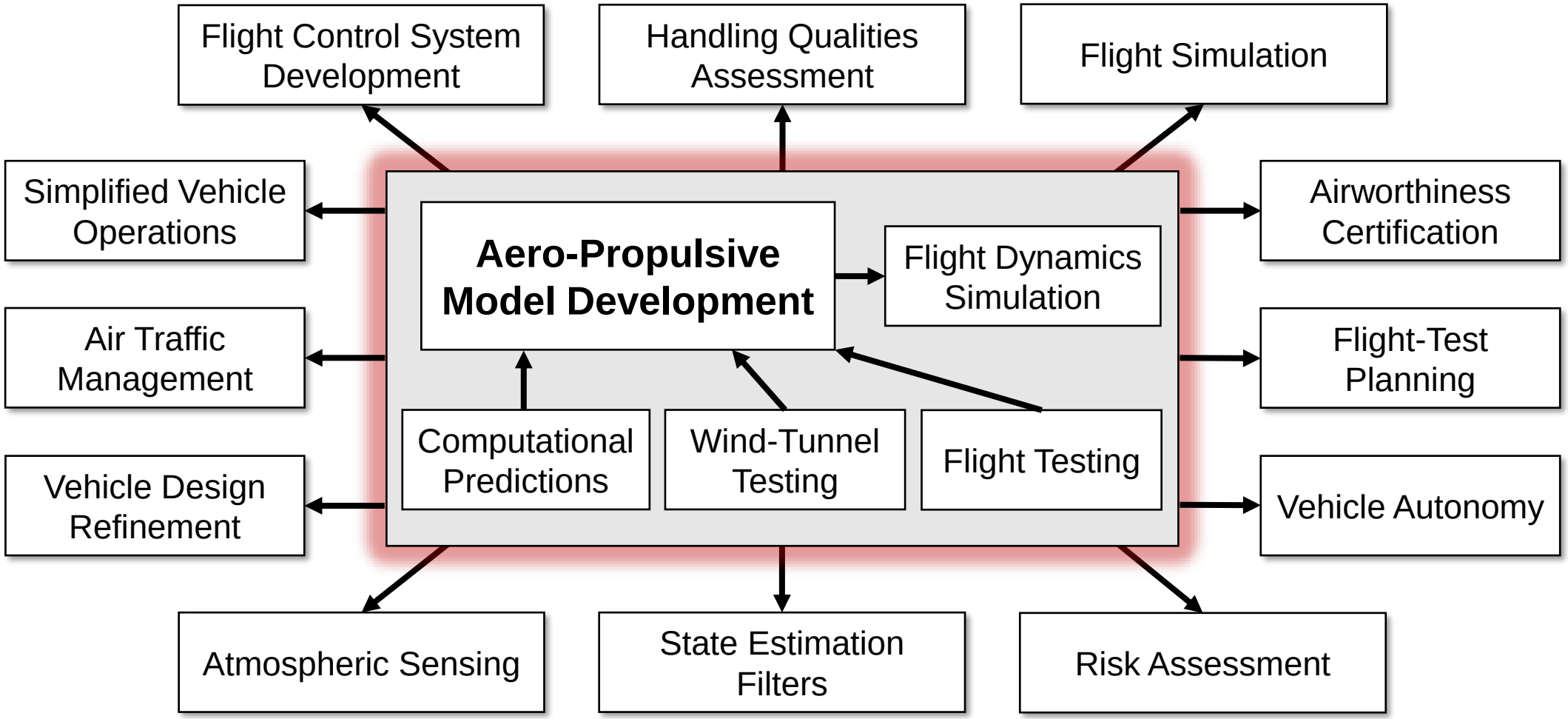
eVTOL vehicle configurations exhibit highly complex, nonlinear aerodynamics

Advanced Air Mobility (AAM)



Motivation for Accurate Aircraft Modeling

System identification is an enabling tool for many other disciplines.



Research applications supported by accurate vehicle model development.

Standard System Identification Approaches



Fixed-Wing Aircraft

- Nondimensional aerodynamic force and moment coefficients
  - C_X (or C_D), C_Y, C_Z (or C_L), C_l, C_m, C_n
  - Normalized by $\frac{1}{2}\rho V^2$, geometry
- Function of $V, \alpha, \beta, \hat{p}, \hat{q}, \hat{r}$ and control deflections
- Computational predictions, wind-tunnel testing, and/or flight testing
- Linear or nonlinear models

Rotary-Wing Aircraft

- Dimensional force and moment parameters (X, Y, Z, L, M, N)
- Function of u, v, w, p, q, r, pilot control inputs, and rotor states
- Computational predictions and/or flight testing
- Linear transfer function or state space models
- Multirotor modeling is similar

Guides the development of eVTOL aircraft modeling strategies

eVTOL Aircraft Modeling Overview

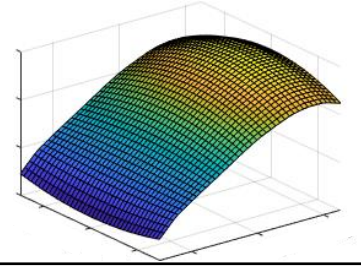
- Conventional methods (e.g., one-factor-at-a-time) fail to efficiently capture the complexity and interactions present in eVTOL aircraft designs
- Several new techniques have been developed for rapid, accurate, statistically-rigorous full-envelope eVTOL aircraft aero-propulsive modeling
- Response surface representations of complex aerodynamics
- Applicable throughout the design process enabling rapid aircraft realization

Scope of eVTOL Aircraft Modeling Technology

Experiment Design
- Design of experiments (DOE)
- Response surface methods (RSM)
- Programmed test inputs (PTI)

Test Facilities
- Various-fidelity computational methods
- Langley 12-Foot Low-Speed Tunnel
- Flight testing

Response Surface ID



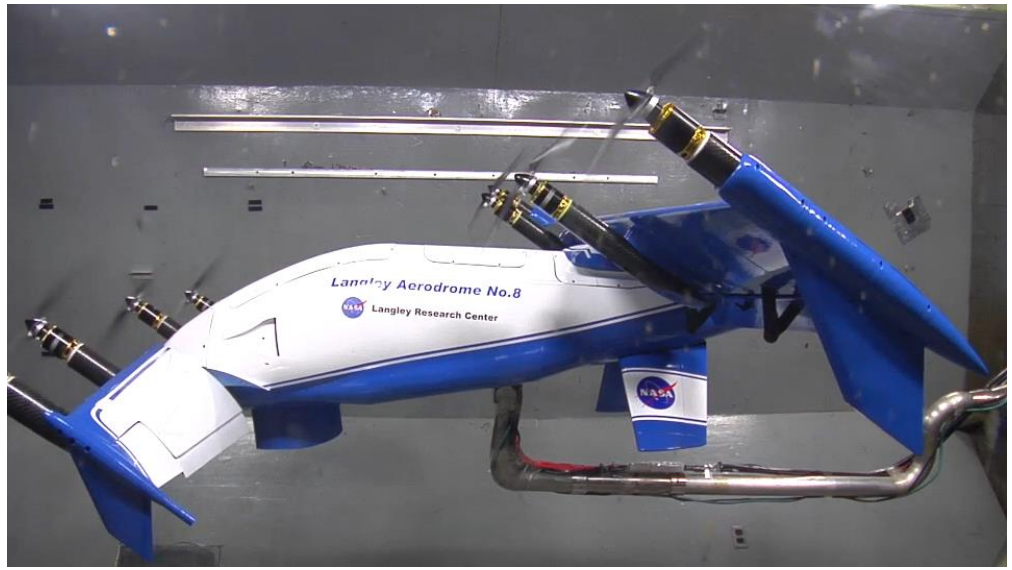
Recent eVTOL Aircraft Aero-Propulsive Modeling Research

NASA LA-8 eVTOL Testbed

- Wind-tunnel/flight test research vehicle
- Tandem tilt-wing configuration
- Distributed electric propulsion
- 63 lbs, 6-foot wingspan
- Significant aero-propulsive coupling
- 20 available control effectors
  - Eight proprotors $(n_1, n_2, \ldots, n_8)$
  - Two tilting wings $(\delta_{w_1}, \delta_{w_2})$
  - Four elevons $(\delta_{e_1}, \delta_{e_2}, \delta_{e_3}, \delta_{e_4})$
  - Four flaps $(\delta_{f_1}, \delta_{f_2}, \delta_{f_3}, \delta_{f_4})$
  - Two ruddervators $(\delta_{r_1}, \delta_{r_2})$



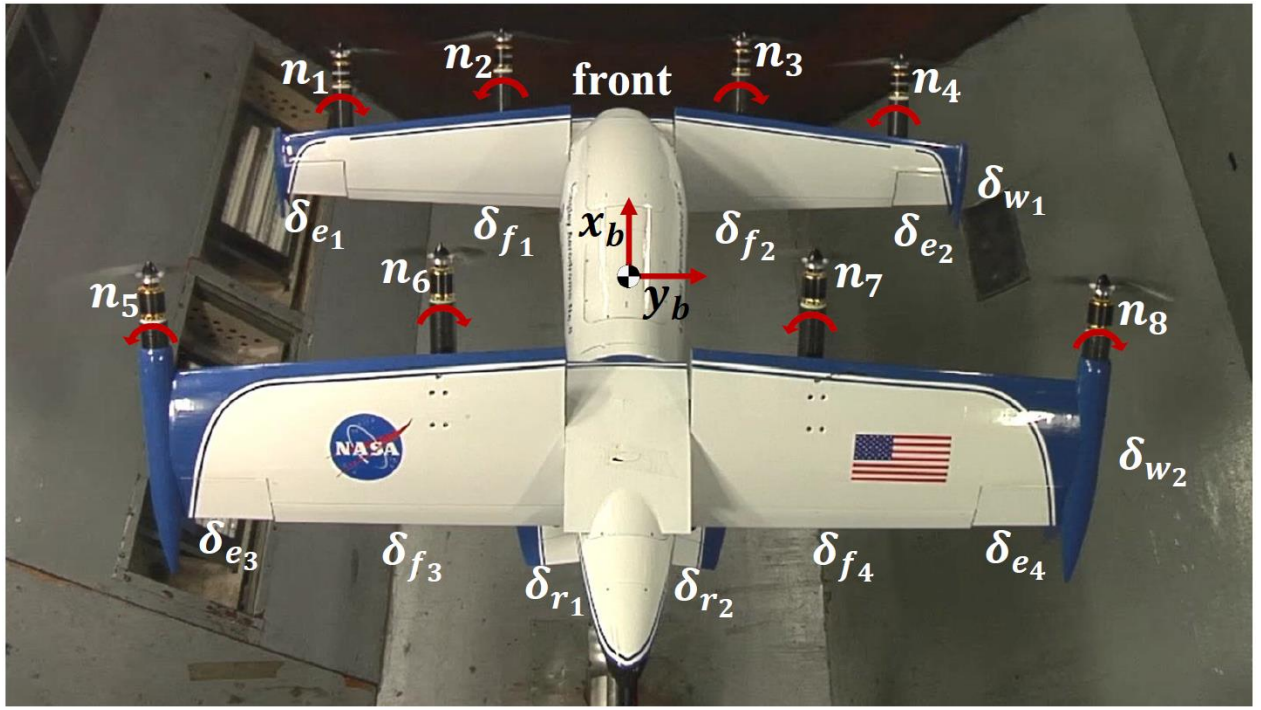
LA-8 flight test.



LA-8 wind-tunnel test.

LA-8 Aircraft Modeling Variable Definitions

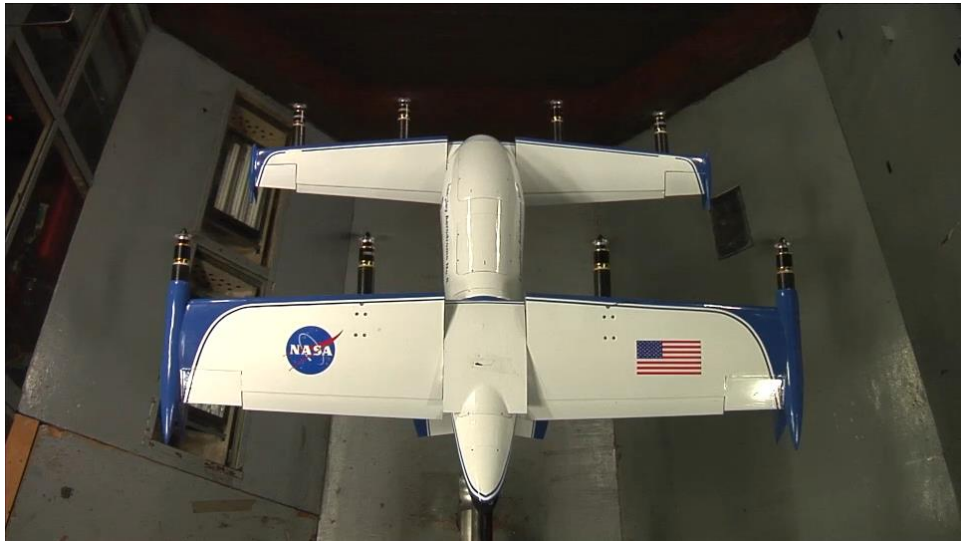
- Response variables
  - Dimensional aero-propulsive forces and moments: X, Y, Z, L, M, N
  - Directly measured in wind-tunnel tests; inferred from other sensors in flight tests
- Explanatory variables
  - Body-axis translational velocity: u, v, w
  - Body-axis angular velocity: p, q, r
  - Control surface deflections: $\delta_{e_1}, \delta_{e_2}, \delta_{e_3}, \delta_{e_4}, \delta_{f_1}, \delta_{f_2}, \delta_{f_3}, \delta_{f_4}, \delta_{r_1}, \delta_{r_2}$
  - Proprotor rotational speed: $n_1, n_2, \ldots, n_8$
  - Wing tilt angles: $\delta_{w_1}, \delta_{w_2}$
- Flight condition variables
  - Airspeed/dynamic pressure: u, V, or $\bar{q}$
  - Altitude/air density: h or ρ
  - Wing tilt angles: $\delta_{w_1}, \delta_{w_2}$



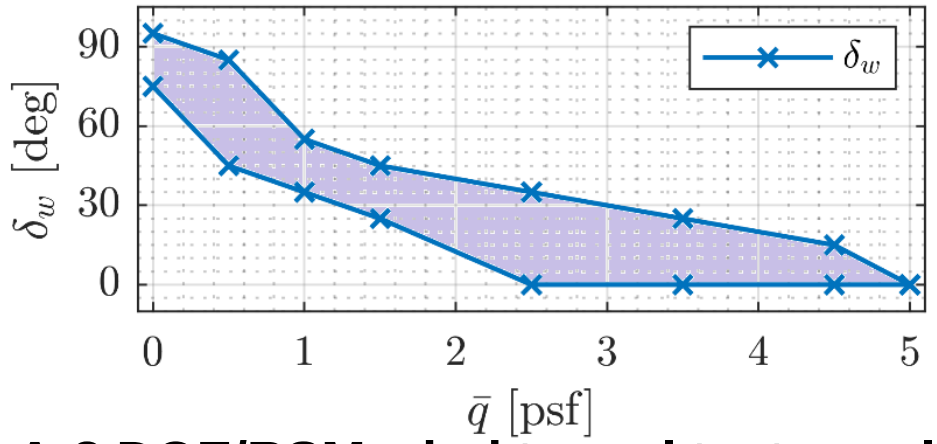
LA-8 control effector definitions.

LA-8 Aero-Propulsive Model Development

- Aero-propulsive models developed from wind-tunnel data
  - Isolated-proprotor test
  - Isolated-airframe test
  - Powered-airframe test
- eVTOL-specific system identification approach
- Nonlinear aero-propulsive models developed at eight dynamic pressure ($\bar{q}$) settings
- Model form tailored to eVTOL vehicles
- Test factor ranges at each freestream velocity reflect the LA-8 flight envelope
- Application of DOE/RSM test techniques



Powered LA-8 DOE/RSM wind-tunnel test.



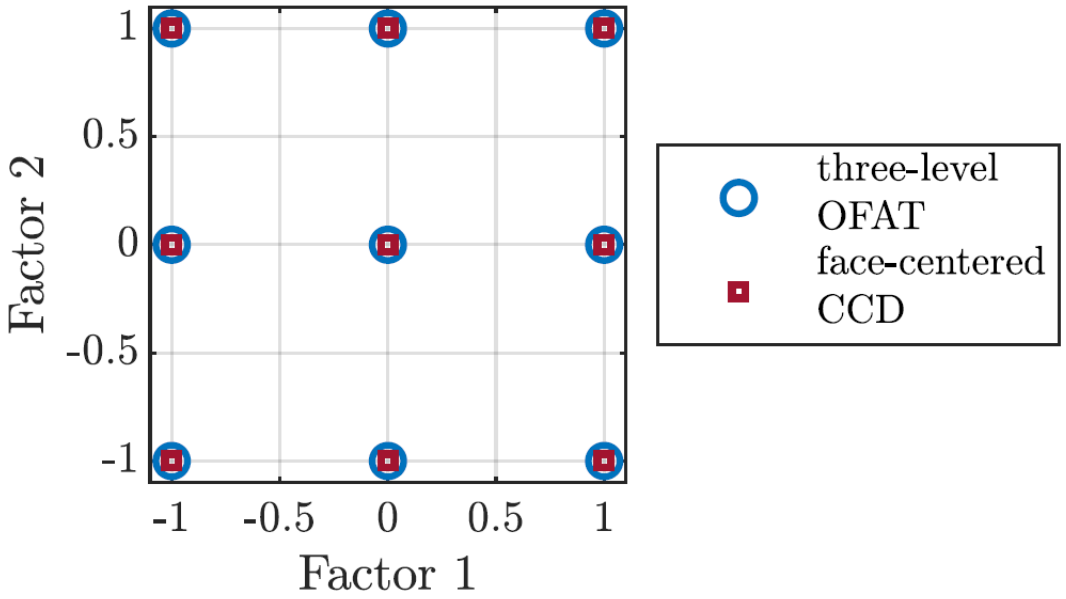
LA-8 DOE/RSM wind tunnel test envelope.

Simmons, B. M., and Murphy, P. C., "Aero-Propulsive Modeling for Tilt-Wing, Distributed Propulsion Aircraft Using Wind Tunnel Data," *Journal of Aircraft*, 2022.

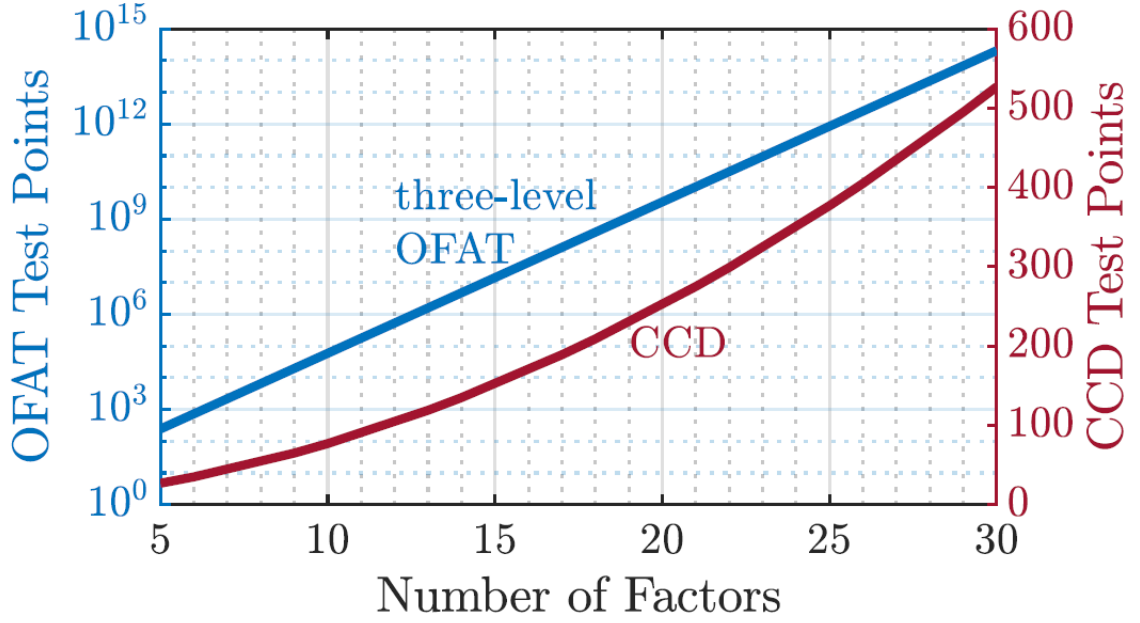
Efficiency Gains Realized Using DOE/RSM

- Three-level one-factor-at-a-time (OFAT) design
- Minimum run resolution V, face-centered central composite design (CCD)

22-factor experiment
OFAT points: 31 billion
CCD points: 299



Two-dimensional design space slice



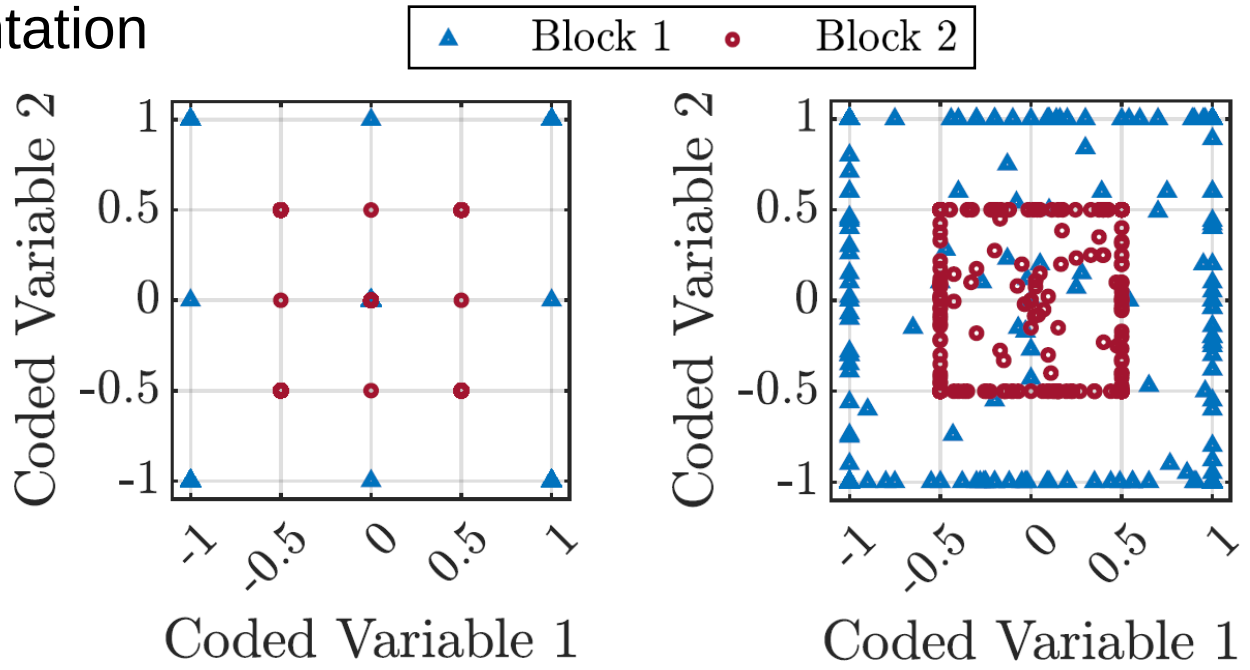
Number of test points

Comparison of three-level OFAT and DOE/RSM experiments.

Example Response Surface Designs

- DOE/RSM designs applied to eVTOL aircraft
  - Nested face-centered central composite design (FCCCD)
  - Nested FCCCD with I-optimal augmentation
  - Nested I-optimal design
- Statistically-designed experiment properties aid modeling
  - Orthogonality
  - Randomization
  - Replication
  - Blocking
  - Sequential testing
- Tremendous efficiency benefits compared to traditional methods

Years → Days



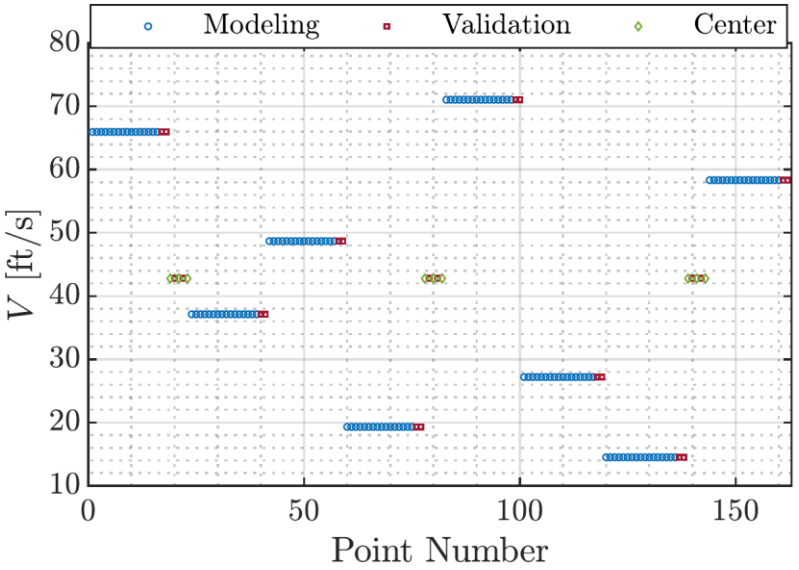
Nested FCCCD **Nested I-optimal**

2D slices of DOE/RSM test matrices.

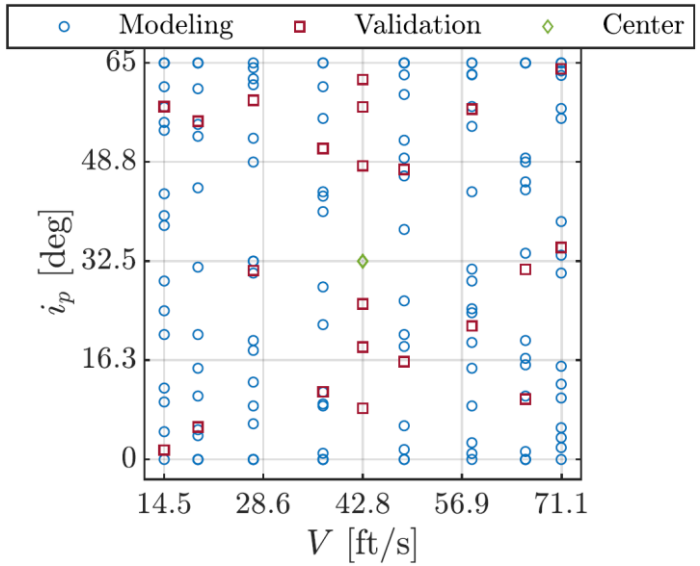
Simmons, B. M., "Evaluation of Response Surface Experiment Designs for Distributed Propulsion Aircraft Aero-Propulsive Modeling," *AIAA SciTech Forum*, 2023.

eVTOL Aircraft Isolated Proprotor Testing

- eVTOL aircraft proprotors experience many operating conditions
- Experiment with a hard-to-change factor (V) – restricted randomization
- Split-plot I-optimal response surface design
- High-fidelity proprotor aerodynamic model

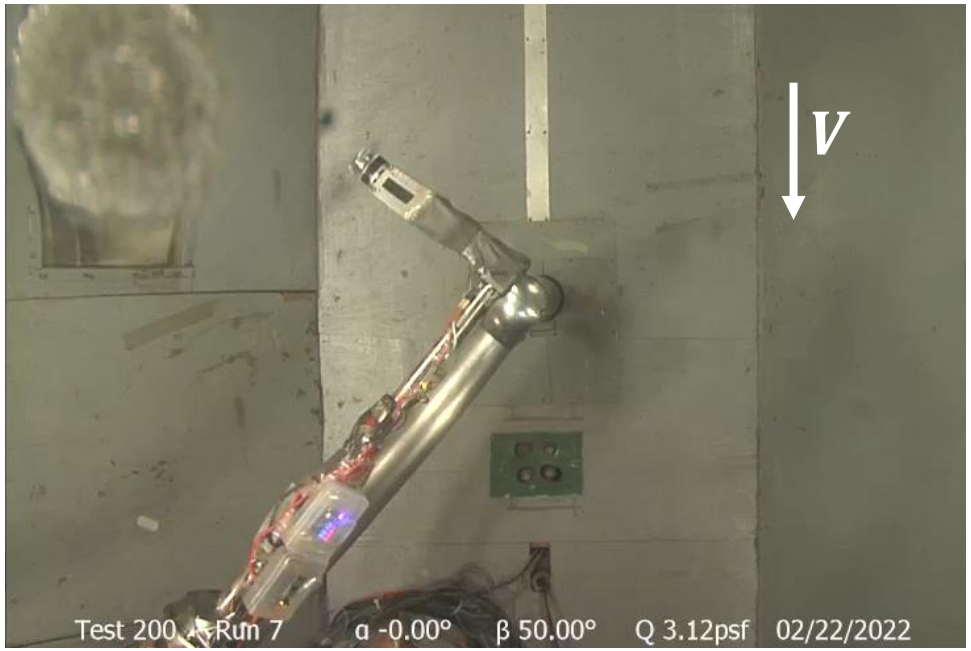


Freestream velocity against point



Incidence against freestream velocity

Sample DOE/RSM proprotor characterization test matrix.

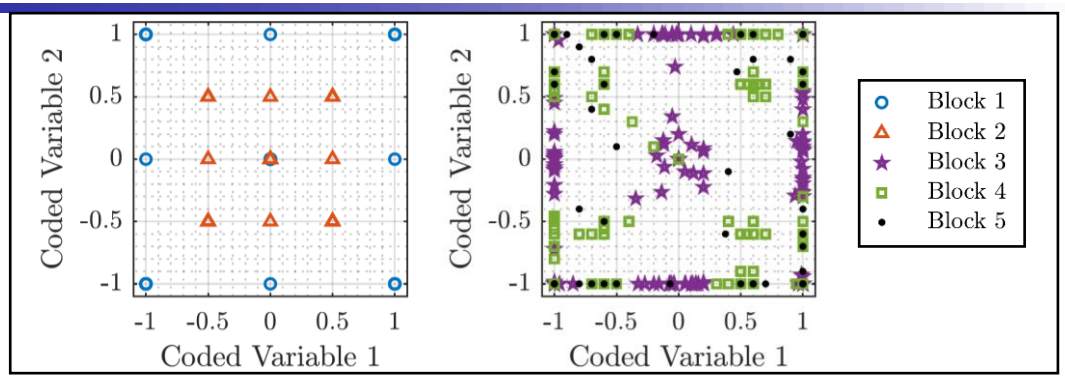


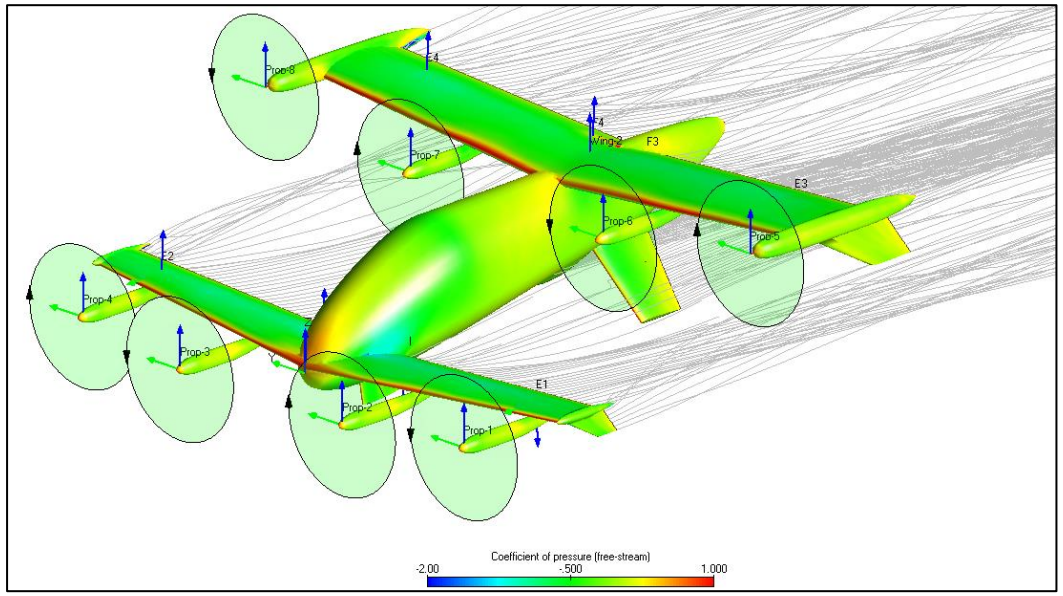
Wind tunnel run (x150 speed).

Simmons, B. M., "Efficient Variable-Pitch Propeller Aerodynamic Model Development for Vectored-Thrust eVTOL Aircraft," *AIAA AVIATION Forum*, 2022.

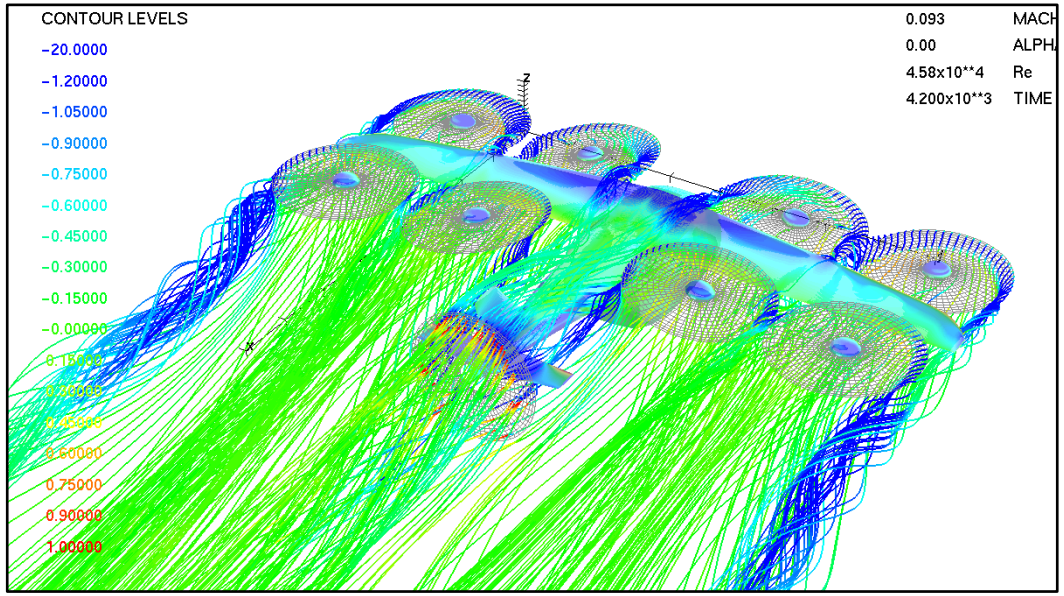
DOE/RSM Applied to Computational Testing

- Similar to wind-tunnel experiments
- Modifications for deterministic data
- OVERFLOW and FlightStream





LA-8 FlightStream solution.



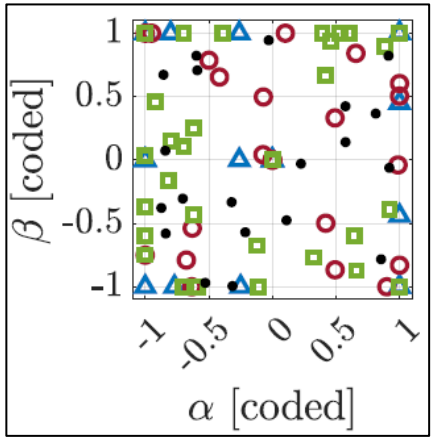
Lift+Cruise OVERFLOW solution.

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 Forum*, 2021.

LA-8 Hybrid DOE/PTI Wind Tunnel Testing

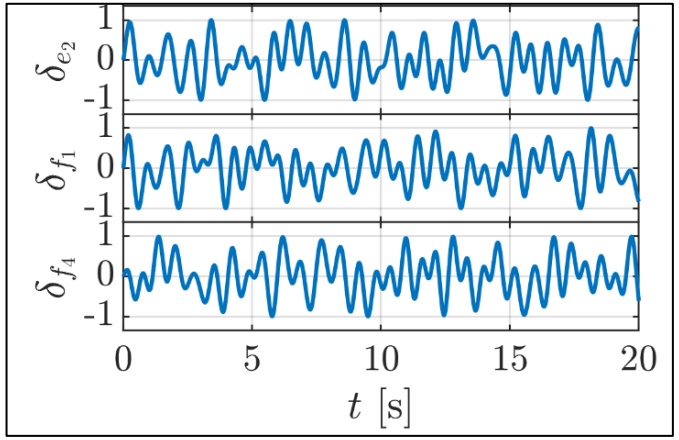
- Hybrid experiment design and wind-tunnel testing strategy
- Simultaneous execution of static DOE/RSM testing and PTIs
- New compound modeling strategy
- Large efficiency increase

Days → Hours



2D slice of the DOE/RSM design.

+



Sample multisine PTI signals.

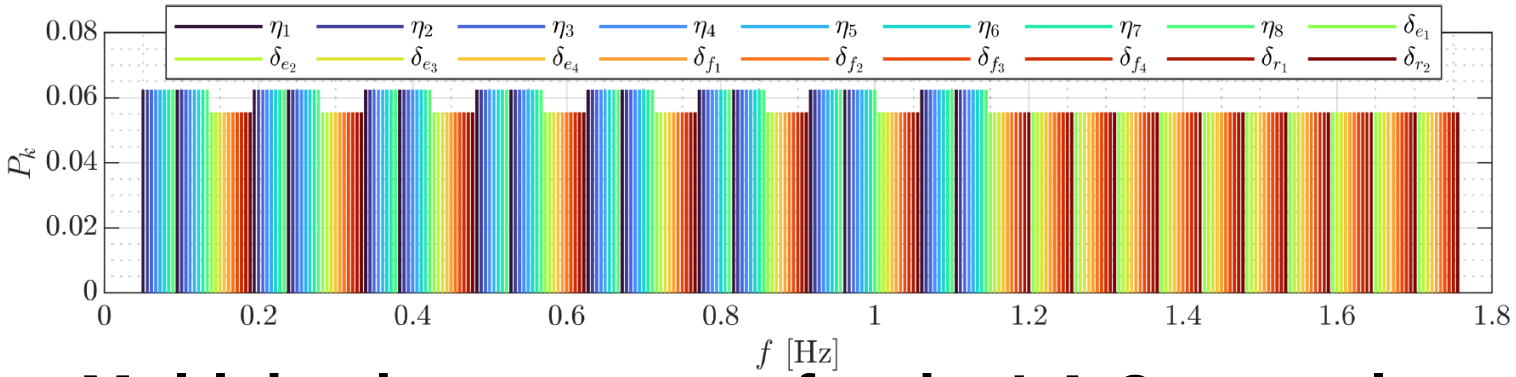


Hybrid DOE/PTI wind-tunnel testing.

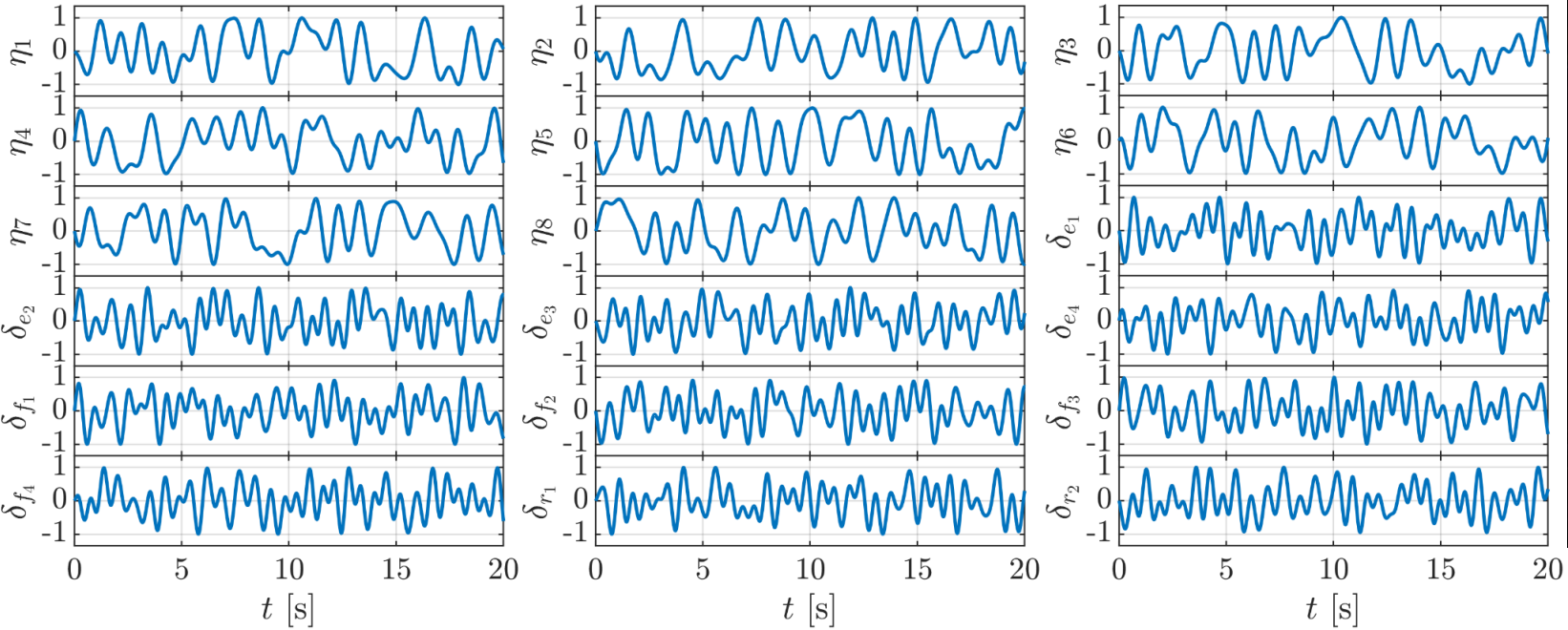
Simmons, B. M., Morelli, E. A., Busan, R. C., Hatke, D. B., and O'Neal, A. W., "Aero-Propulsive Modeling for eVTOL Aircraft Using Wind Tunnel Testing with Multisine Inputs," *AIAA AVIATION Forum*, 2022.

LA-8 Dynamic Input Design

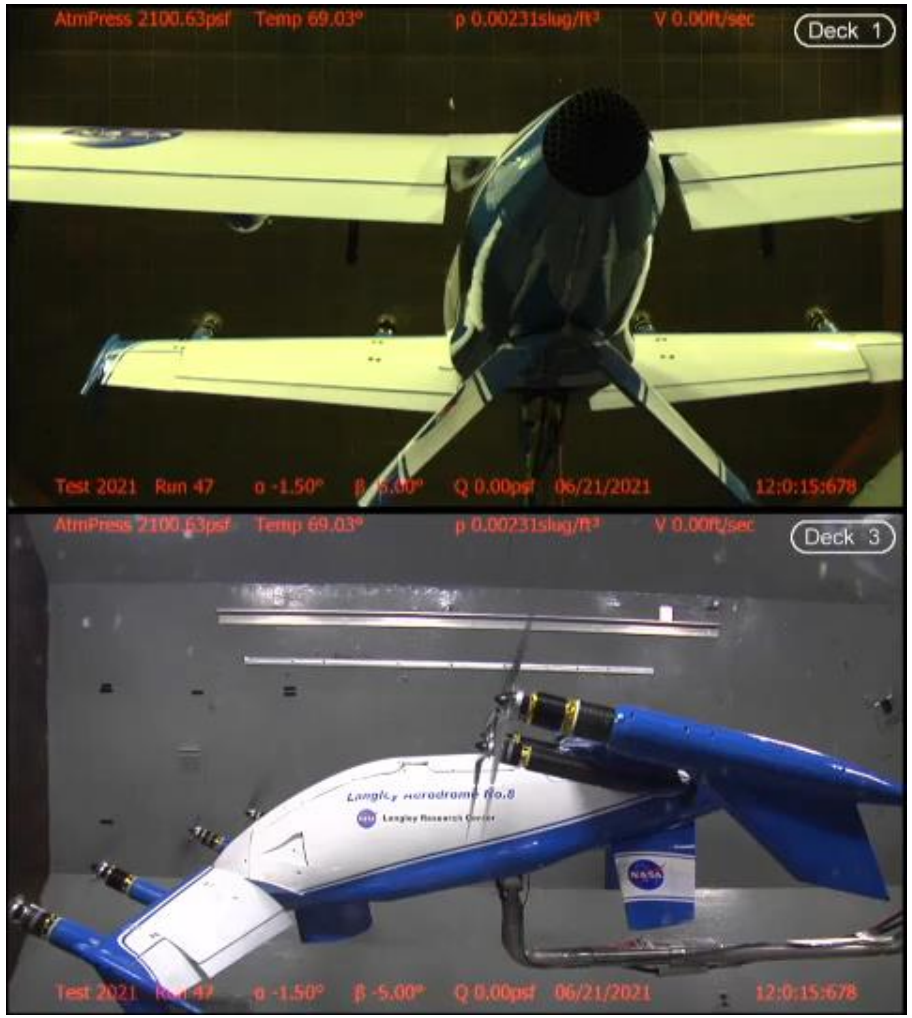
$$\boldsymbol{u_j} = \sum_{k \in K_j} A\sqrt{P_k} \sin\left(\frac{2\pi k \boldsymbol{t}}{T} + \phi_k\right)$$



Multisine input spectra for the LA-8 controls.



Normalized LA-8 control effector multisine inputs.



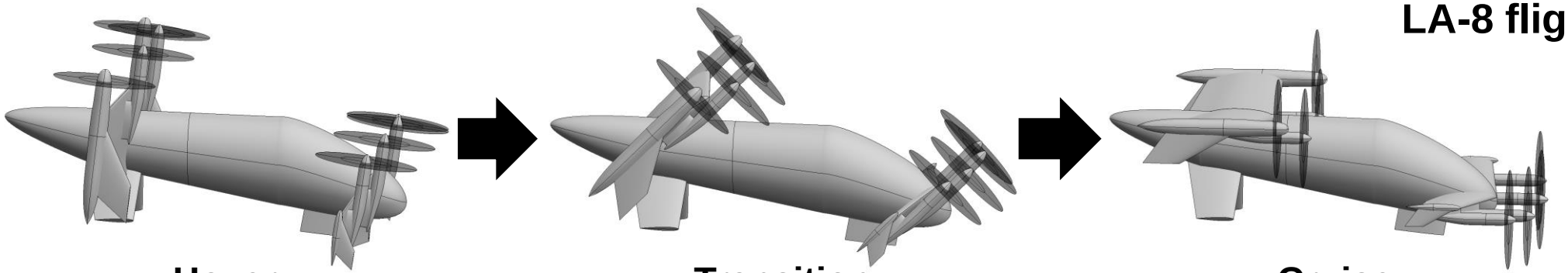
LA-8 wind-tunnel testing with multisine inputs.

eVTOL Flight-Test System Identification Approach

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



LA-8 flight test.



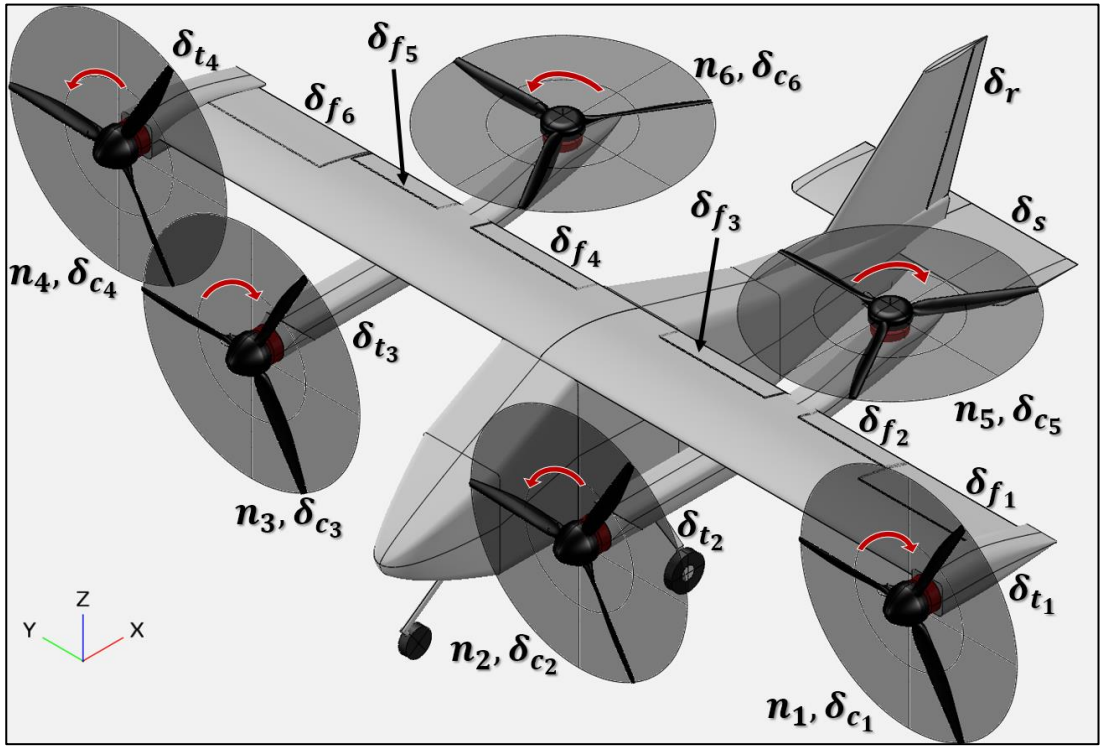
Complements safe envelope expansion flight testing

Simmons, B. M., "System Identification Approach for eVTOL Aircraft Demonstrated Using Simulated Flight Data," *Journal of Aircraft*, 2023

Current Research using the RAVEN eVTOL Aircraft

RAVEN eVTOL Vehicle

- RAVEN – **R**esearch **A**ircraft for e**V**TOL **E**nabling Tech**N**ologies[1]
- Tilt-rotor 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 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)
  - Rudder (δ_r)
- Built for modeling and controls research



RAVEN control effector definitions.

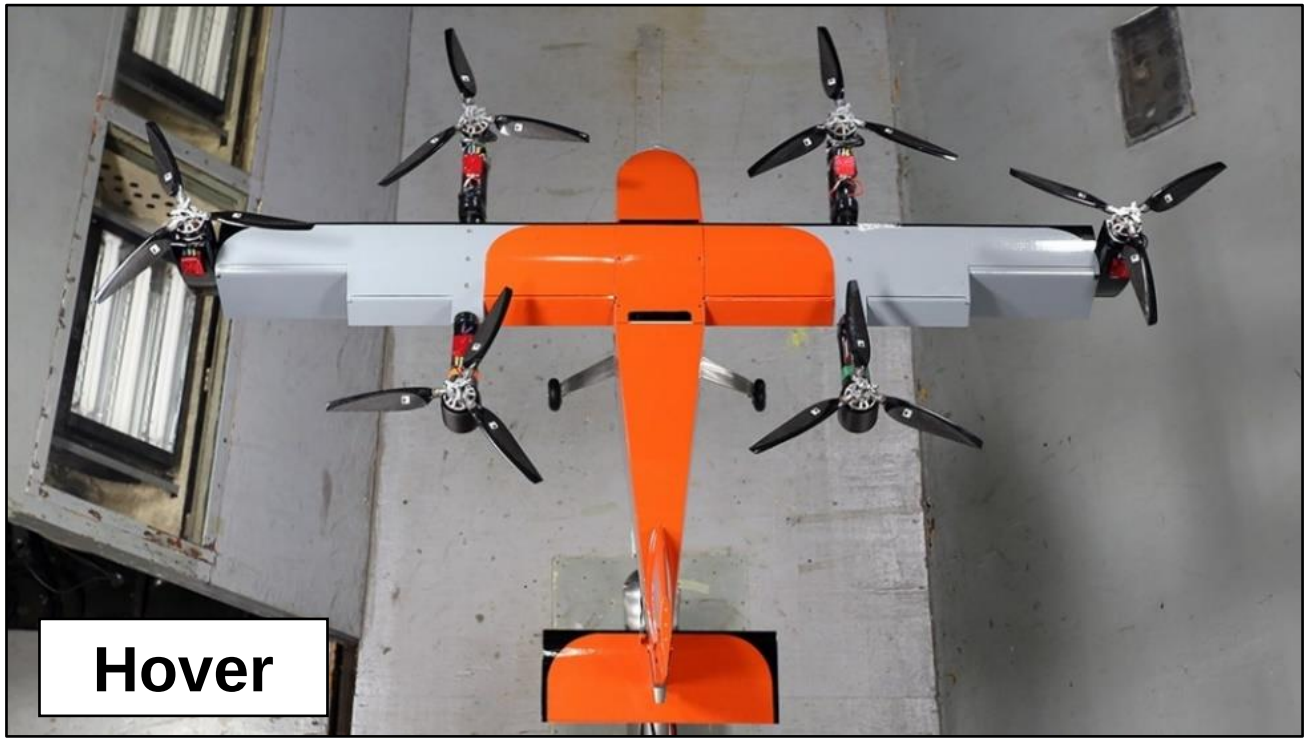
German, B. J., Jha, A., Whiteside, S. K. S., and Welstead, J. R., "Overview of the Research Aircraft for eVTOL Enabling techNologies (RAVEN) Activity," *AIAA AVIATION Forum*, 2023.

RAVEN SWFT Vehicle

SWFT = **S**ubscale **W**ind-Tunnel and **F**light **T**est

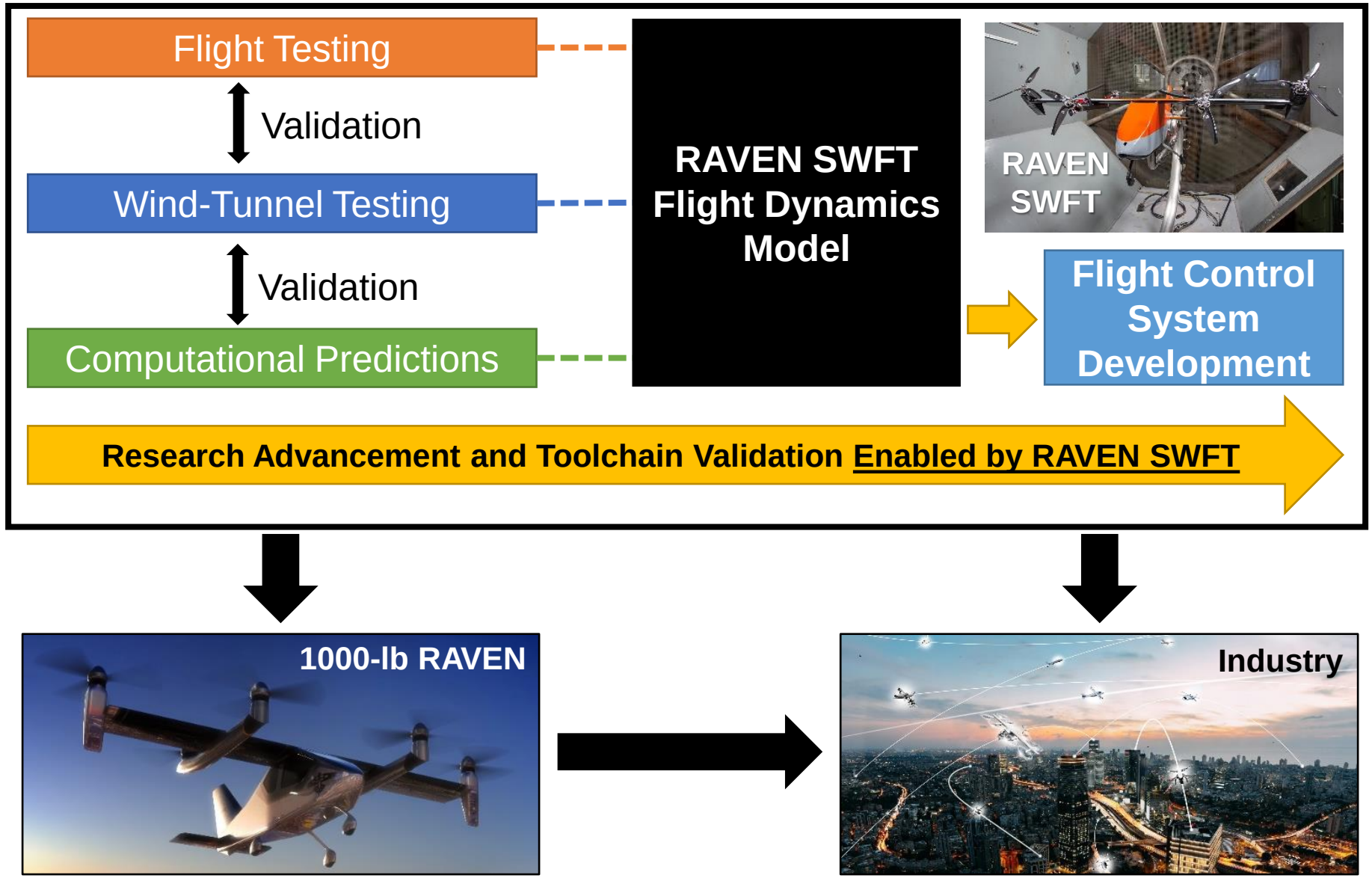
- Wind-tunnel and flight-test research
- Similar in scale and utility to the NASA LA-8
- 28.6% scale version of 1000-lb vehicle
- 37 lbs, 5.7 ft wingspan, 19.5 in diam. proprotors







RAVEN SWFT Modeling and Controls

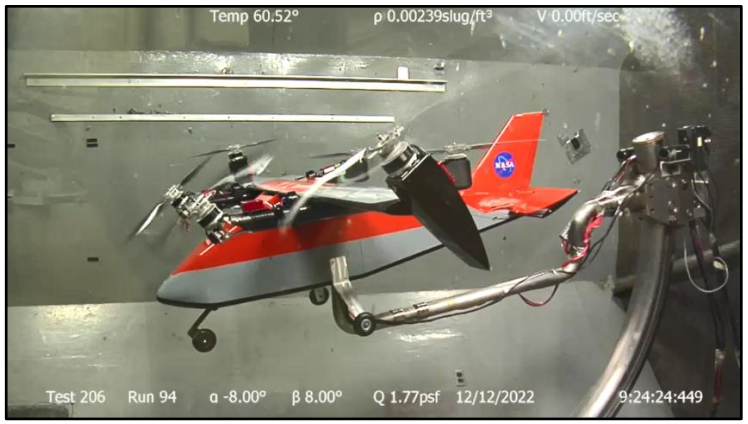


RAVEN SWFT Wind-Tunnel Testing

Langley 12-Foot Low-Speed Tunnel

- Isolated proprotor test (Feb-22)
- Static full-airframe test (Nov-22)
- Dynamic testing (in progress)





Proprotor **Powered-airframe**

RAVEN SWFT wind tunnel tests.

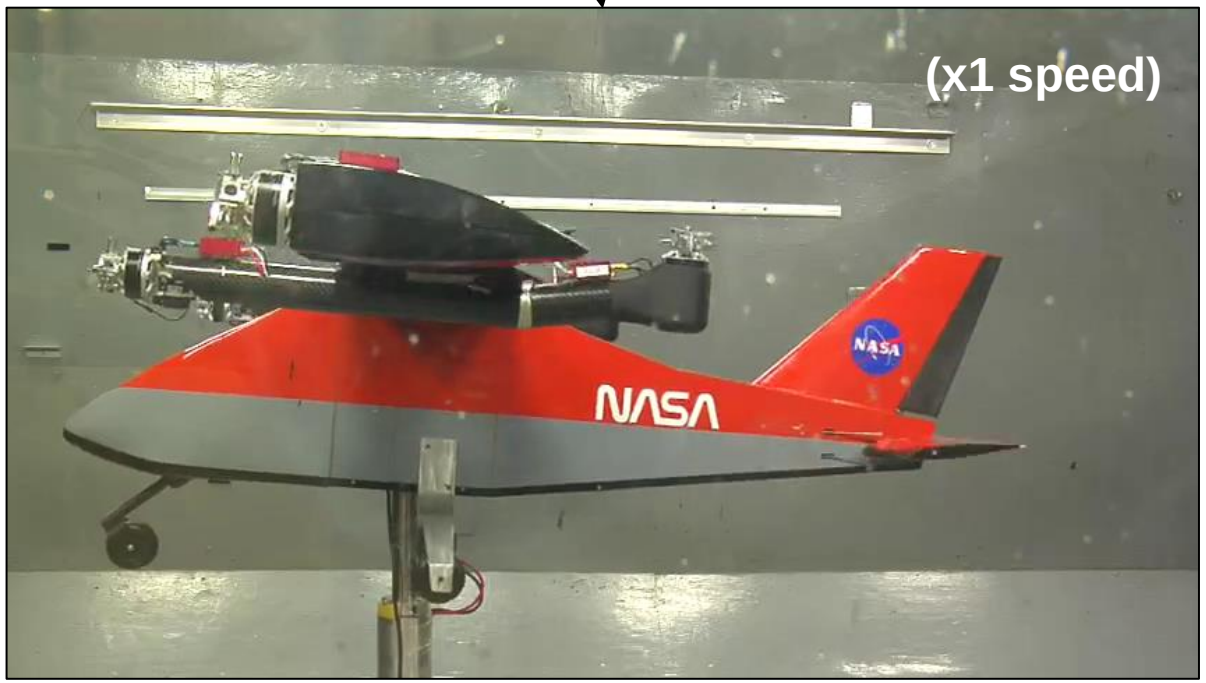
Benefits

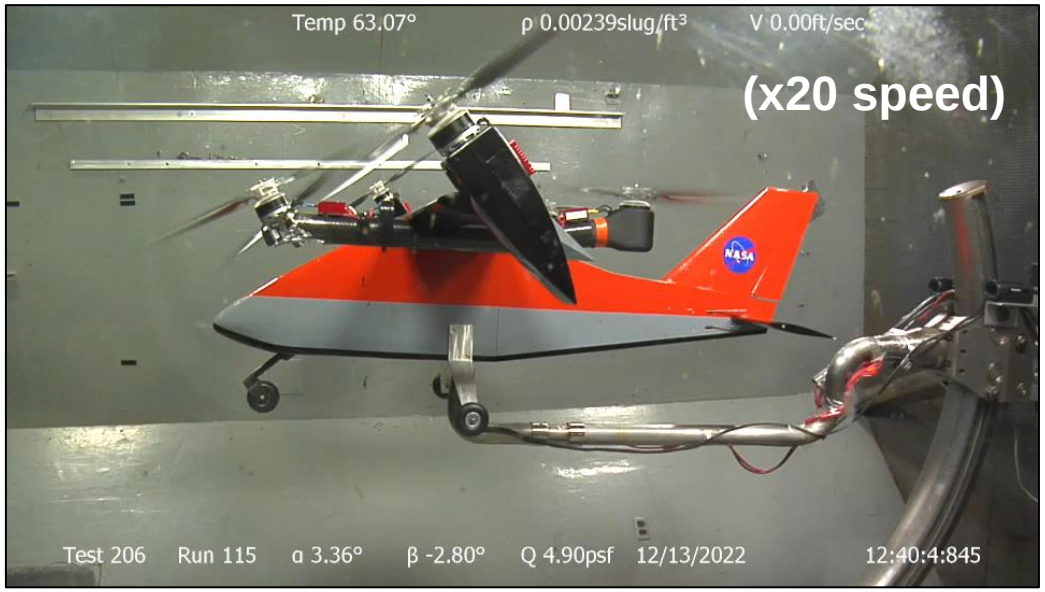
- Flight simulation development
- Model-based flight control system design
- Enables future flight-test research
- Validation of computational aerodynamic prediction tools
- eVTOL aero-propulsive modeling research advancements
- Data/models that can be published

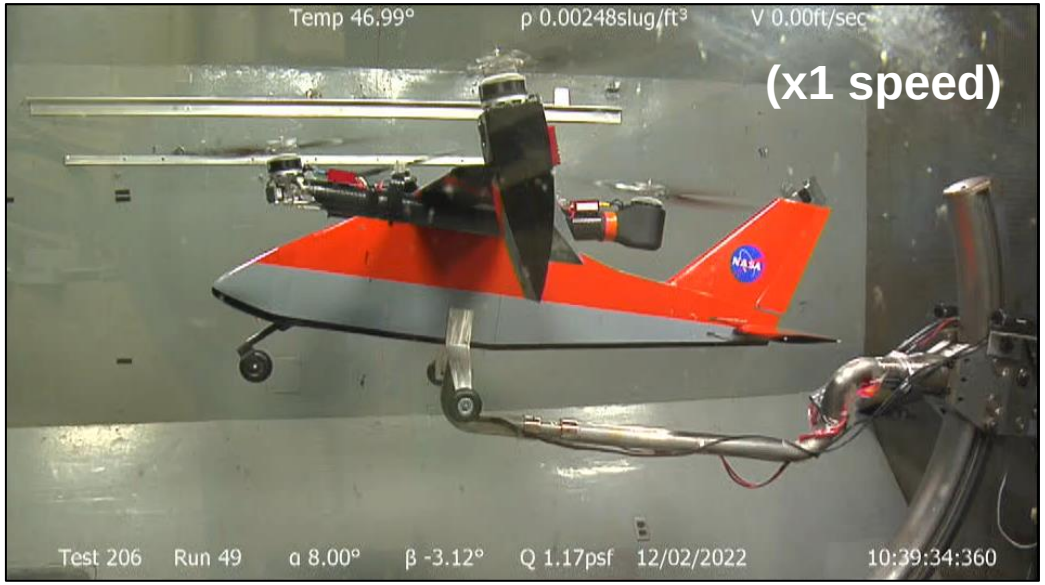
Simmons, B. M., and Busan, R. C., "Statistical Wind-Tunnel Experimentation Advancements for eVTOL Aircraft Aero-Propulsive Model Development," *AIAA SciTech Forum*, 2024, To be published.

RAVEN SWFT Wind-Tunnel Testing

- Static DOE/RSM testing
- Static DOE/RSM-PTI testing
- Three degree-of-freedom (3DOF) testing

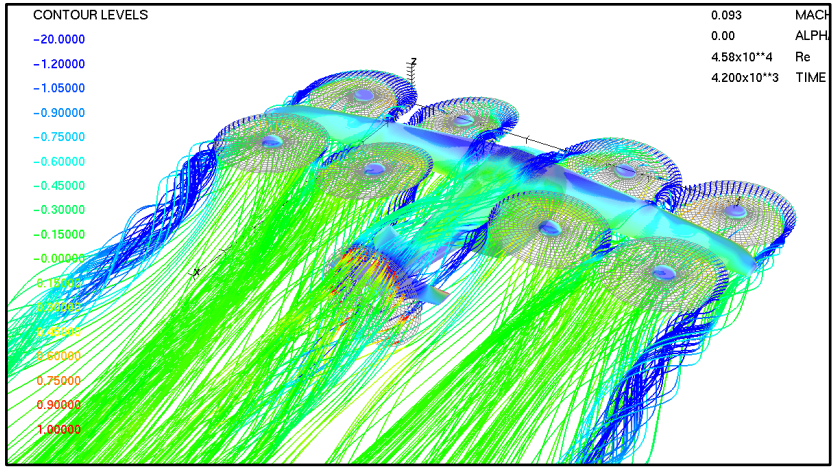






Concluding Remarks

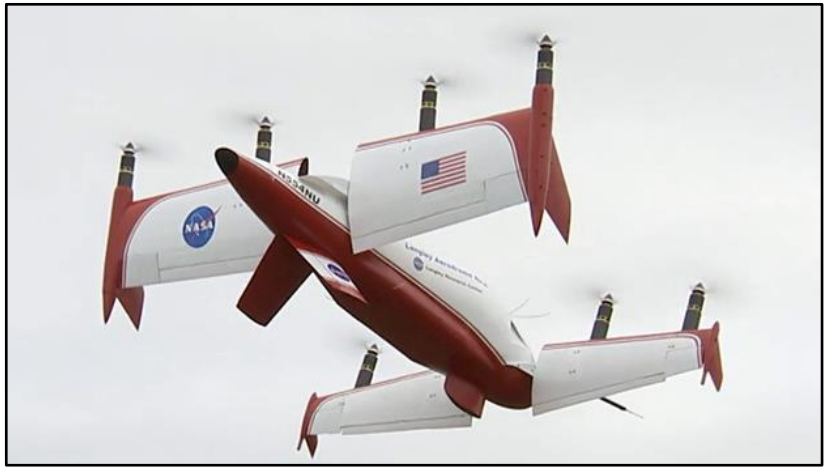
- eVTOL aircraft present new aero-propulsive modeling challenges
- Multiple efficient experiment design and aero-propulsive modeling strategies for eVTOL aircraft have been successfully demonstrated
- Significant progress in modeling approaches for complex aircraft
- Active research is further refining eVTOL vehicle modeling techniques
- Techniques can be applied for many current and future eVTOL vehicles
- Strong emphasis on public release of eVTOL aircraft data and technology



Lift+Cruise CFD simulation.



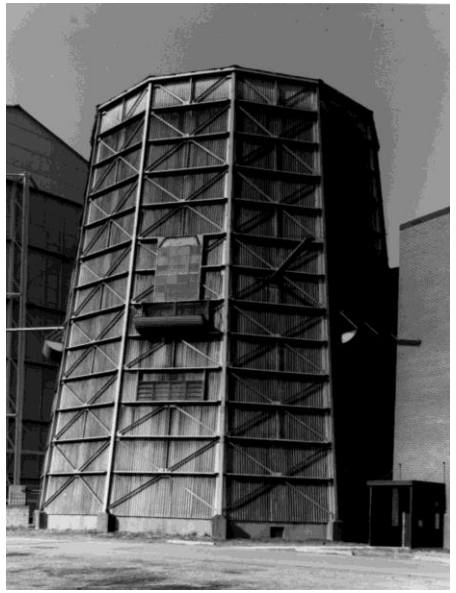
RAVEN-SWFT wind-tunnel test.



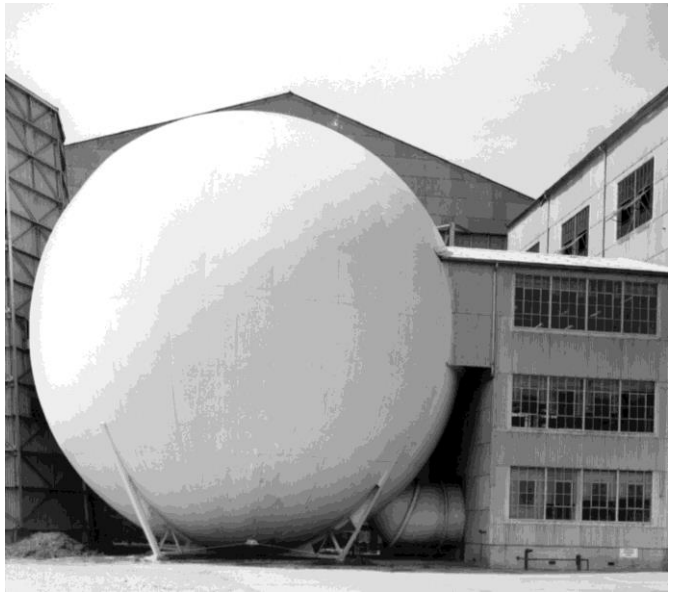
LA-8 flight test.

Look Ahead: NASA Langley FDRF

- Flight Dynamics Research Facility (FDRF)
- Scheduled to open in January 2025
- Replacing and combining/expanding the capabilities of the:
  - 20-Foot Vertical Spin Tunnel (VST)
  - 12-Foot Low-Speed Tunnel (LST)



20-Foot VST



12-Foot LST



FDRF construction progress (October 18, 2023)

Questions/Discussion – Thank you for attending.

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Collaborators: Kasey Ackerman, Pieter Buning, Patrick Murphy, Eugene Morelli, Ronald Busan, Steven Geuther, Wes O'Neal, David Hatke

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