Aero-Propulsive Modeling for eVTOL Aircraft Using Experimental Data

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Contents

- Research motivation, background, and challenges
- Overview of eVTOL aircraft modeling approach
- Wind-tunnel, CFD, and flight-test applications
- 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
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

LA-8

RAVEN

Lift+ Cruise
Modeling From Experimental Data

General process for aircraft system identification

Motivation -> Modeling Objectives -> Application

Experiment Design -> Adequate Model

Test Execution -> Data Processing

Model Validation -> Model 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

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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 vehicle configurations exhibit highly complex, nonlinear aerodynamics*

900+ known eVTOL aircraft concepts!
Reference: [https://evtol.news/aircraft](https://evtol.news/aircraft)
Advanced Air Mobility (AAM)

Credit: NASA
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 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: $\delta_{e1}, \delta_{e2}, \delta_{e3}, \delta_{e4}, \delta_{f1}, \delta_{f2}, \delta_{f3}, \delta_{f4}, \delta_{r1}, \delta_{r2}$
  - Proprotor rotational speed: $n_1, n_2, ..., n_8$
  - Wing tilt angles: $\delta_{w1}, \delta_{w2}$

- **Flight condition variables**
  - Airspeed/dynamic pressure: $u, V$, or $\bar{q}$
  - Altitude/air density: $h$ or $\rho$
  - Wing tilt angles: $\delta_{w1}, \delta_{w2}$

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

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)

Two-dimensional design space slice

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

Number of test points

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

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

Wind tunnel run (x150 speed).

Freestream velocity against point
Incidence against freestream velocity
Sample DOE/RSM proprotor characterization test matrix.

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.

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.

LA-8 Dynamic Input Design

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

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

Current Research using the RAVEN eVTOL Aircraft
RAVEN eVTOL Vehicle

• RAVEN – Research Aircraft for eVTOL Enabling TechNologies¹

• Tilt-rotor eVTOL configuration with six variable-pitch proprotors

• Vehicles at different scales

• 24 independent control effectors
  ▪ Six proprotor speeds ($n_1, n_2, ... , n_6$)
  ▪ Six collective angles ($\delta_c_1, \delta_c_2, ... , \delta_c_6$)
  ▪ Four tilt angles ($\delta_t_1, \delta_t_2, \delta_t_3, \delta_t_4$)
  ▪ Six flaperons ($\delta_f_1, \delta_f_2, ... , \delta_f_6$)
  ▪ Stabilator ($\delta_s$)
  ▪ Rudder ($\delta_r$)

• Built for modeling and controls research

RAVEN SWFT Vehicle  

- 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

SWFT = Subscale Wind-Tunnel and Flight Test
RAVEN SWFT Modeling and Controls

RAVEN SWFT Flight Dynamics Model

Wind-Tunnel Testing

Validation

Computational Predictions

Flight Testing

RAVEN SWFT

Flight Control System Development

Research Advancement and Toolchain Validation Enabled by RAVEN SWFT

1000-lb RAVEN

Industry
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)

**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

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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)

FDRF construction progress (October 18, 2023)
Questions/Discussion – Thank you for attending.

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eVTOL Aircraft Modeling References


