X-57 Knowledge Transfer and Wrap-Up

Sean Clarke, X-57 Principal Investigator
Nick Borer, X-57 Deputy Principal Investigator
Vince Schultz, X-57 Deputy Project Manager

Knowledge Transfer is Integral to X-57 Objectives

Objective	Success Criteria
OBJ-1: Develop distributed electric propulsion (DEP) **airworthiness standards with industry**.	Actively influence **civil airworthiness standards** development to address the critical DEP-related gaps related to public certification rules.
OBJ-2: **Increase regulators' proficiency** in the development of airworthy electric aircraft and distributed electric propulsion systems.	**Complete a Flight Readiness Review** of an aircraft with a complex, integrated DEP system. Publish X-57 "Airworthiness Validation Plan," which **maps NASA FRR artifacts to FAA airworthiness documents**.
OBJ-3: Share X-57 **integrated DEP design & lessons learned with industry and academic stakeholders**.	Conduct yearly technical progress sessions at **key aviation conferences and workshops**. Provide access to **technical reports, major design reviews, and flight results** on the X-57 technical data website.
OBJ-4: Provide a **reference vehicle for DEP** technology advancement.	**Publish X-57 design artifacts** such as analyses, instrumented flight data, outer mold line data file, in-flight DEP acoustic profile.

Knowledge transfer focused on needs of industry, government (regulators), and academia

Rules and Standards Development

- 14 CFR Part 23 (Civil Airworthiness Standards for Normal Category Airplanes) in 2017 created new opportunity for faster adoption of new technologies
  - Move from prescriptive to performance-based requirements
  - Use of consensus standards as means of compliance
- X-57 (then CEPT in formulation) used as one of three examples in FY15 FAA "stress test" to determine if new performance-based rules categories were adequate
  - 14 CFR 23.2110(b) associated with use of propellers for lift augmentation directly resulted from early FAA engagement
- X-57 SMEs helped develop consensus standards for DEP
  - ASTM Committee F39 on Aircraft Systems
  - ASTM Committee F44 on General Aviation

Rules and Standards: DEP CTOL Aircraft

X-57 *Airworthiness Validation Plan* engaged FAA Designated Engineering Representatives to identify applicability of civil airworthiness rules and determine gaps in rules and standards for DEP aircraft to help target standards development activities

NASA/CR–20220015049

X-57 Maxwell Airworthiness Validation Plan

22%

14 CFR §35
PROPELLERS

20%

Special Conditions

X-57 Airvolt testing

44%

14 CFR §23
NORMAL CATEGORY AIRPLANES

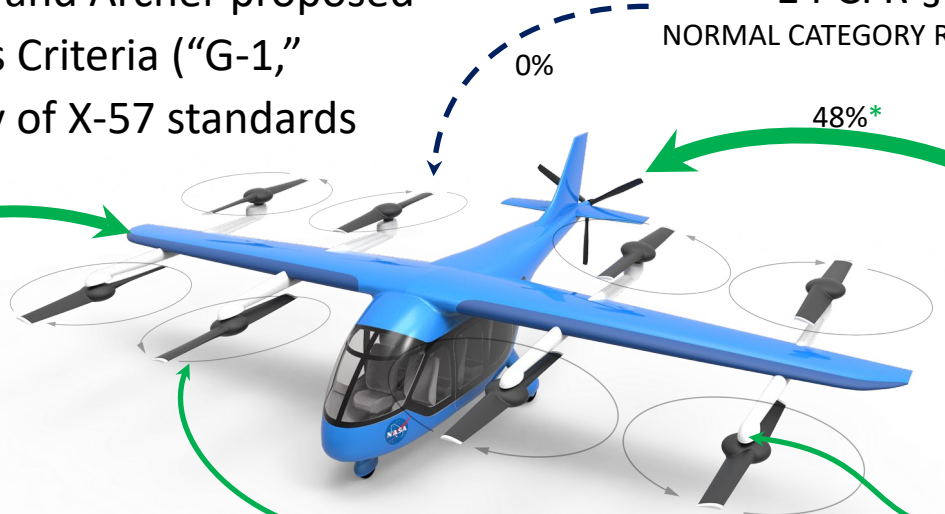
13%

14 CFR §33
AIRCRAFT ENGINES

X-57 has had early and persistent impact for development of standards associated with electric propulsion and distributed propulsion airworthiness

Rules and Standards: eVTOL Aircraft

Applicable rules from Joby and Archer proposed Special Class Airworthiness Criteria ("G-1," 2022) shows transferability of X-57 standards efforts in related domains



*X-57 Applicable

Early eVTOL developers using flexibility of performance-based rules and associated consensus standards from committees where X-57 team has been very active

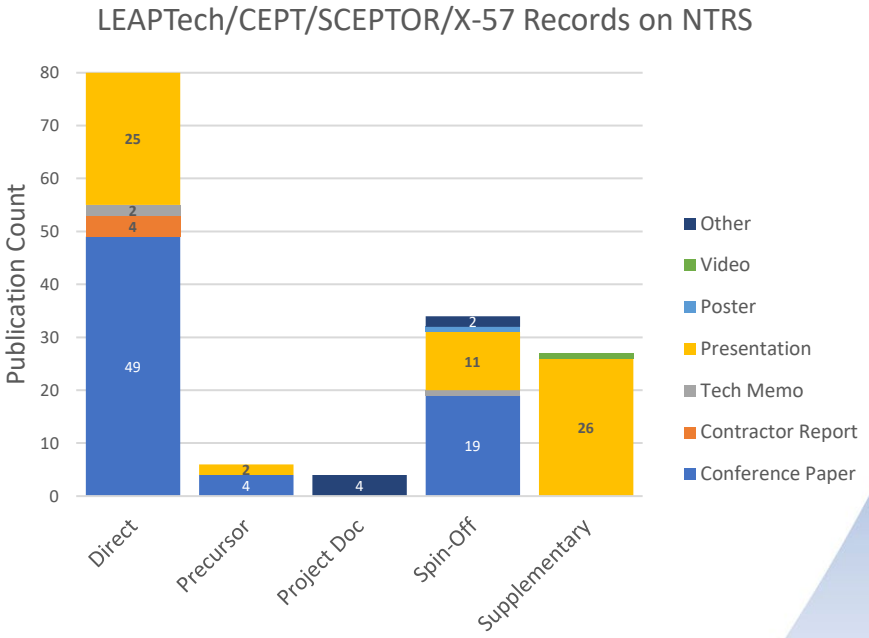
(Partial List of) X-57 Engagement in Consensus Standards

Topic	Subcommittee	Standard	Status
Electric Engines*	ASTM F39.05	ASTM F3338	Standard in place, continuous improvement
Energy Storage	ASTM F39.05, F44.40	Work in progress (F39.05 WK56255)	Stalled; OEMs going with special conditions
Traction System Integration	ASTM F44.40	ASTM F3239	Standard in place, continuous improvement
Distributed Propulsion	ASTM F44.40	Work in progress (WK83536)	Item in work, initial ballots sent
Minimum Flight Speed	ASTM F44.20	ASTM F3180, F3179	Discussed but no proposal yet
Critical Loss of Thrust	ASTM F44.20	ASTM F3173, F3179	Discussed but no proposal yet

*Regulators use “engine” and not “motor” because “engines” are considered a *product* that requires *type certification*

Publicly-Accessible Data and Reports through 1/2024

- X-57 team members have participated in dozens of conferences, forums, and symposia as speakers, panelists, and authors of technical papers
  - AIAA Aviation and SciTech Forums (2014+)
  - IEEE Transportation Electrification Conference & Expo/AIAA Electrified Aircraft Technology Symposium (2016+)
  - … and many others!
- Directly authored 80 technical records that have been archived on NTRS *prior to February 2024*
  - Project PDR, CDR, and geometry model on X-57 technical publications site but not on NTRS



Direct: Original X-57 research products intended for public forums
Precursor: Prior work that directly influence X-57 formulation
Project Doc: Internal project document later released to public
Spin-off: Selected NASA works using X-57 as a reference platform
Supplementary: Public outreach material that includes X-57

Project Archives and Upcoming Events

Papers and Data	Events	Master TM	Online Archive
• **1,346 project documents** retained as permanent records for subproject archives • **80 original public research products** available on NTRS • **20 publications** planned for conferences in 2024 & 2025 • **CFD aero database** and associated TM to be published • **High-lift propeller wind tunnel database** and associated TM to be published • **Geometry model** published	• **ASTM F44 X-57 Workshop** (Cologne, April 2024) • **AIAA Aviation/ EATS Forum** (Las Vegas, July-August 2024) • **ICAS 2024** (Florence, September 2024)	• **Four-volume NASA Tech Memo released by end of FY24** • *Volume 1*: full project bibliography • *Volume 2*: public project reports (101) • *Volume 3*: reports with data rights restrictions (43) • *Volume 4*: records with export restrictions (20)	• Publicly-available records on **NTRS** • Records with restricted data on **NTRS-R** • Data (aero, wind tunnel, geometry) on **data.nasa.gov** • Public-facing website with links publicly-available information: https://nasa.gov/x57/technical/

Comprehensive suite of technical records available to the public and the U.S. Government

Remaining Gaps in Public DEP Airworthiness Standards

High-Lift Propellers & Low-Speed Handling

- Means of compliance for stall speed determination with HLPs [14 CFR §23.2110(b)]

Performance after Critical Loss of Thrust

- Determination of critical loss of thrust and associated flight performance (e.g., 14 CFR §23.2115 [takeoff], §23.2120 [climb], §23.2135 [controllability])

Distributed Power System

- Continued development of consensus standards for electric propulsion (e.g., ASTM F3338) and distributed propulsion (ASTM F44.40 WK83536)

Aero-Structural-Propulsive Interactions

- Means to show thin, flexible, aero-propulsive wings are free of aeroelasticity and whirl flutter concerns (e.g., compliance with §23.2245 [aeroelasticity] for DEP aircraft)

No publicly accepted means of compliance associated with distributed propulsion

Higher, Ever Higher

"What has hitherto done, however, has by no means exhausted the field of electrical research. It has rather opened up that field, by pointing out subjects of enquiry, and furnishing us with means of investigation."

--James Clerk Maxwell (1873)


NASA
MAXWELL
X-57
ELECTRIC AIRPLANE

Assorted Bibliography

Collection of bibliographies from other sections – may contain duplicates

Some items are still being released but are planned to be archived in master TM described on chart 8 of this presentation

Power and Command System

- Public papers and presentations
  - LEAPTech HEIST Power Architecture and Testing [NTRS: 20150022383]
  - Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator [NTRS: 20160010157]
  - Design of an Electric Propulsion System for SCEPTOR [NTRS: 20160007774]
  - X-57 Power and Command System Design [NTRS: 20170005797]
  - Driving Design Factors for Safe, High Power Batteries for Space Applications [NTRS: 20180004170]
  - X-57 Maxwell Battery from Cell Level to System Level Design and Testing [NTRS: 20180005737]
  - Battery Evaluation Profiles for X-57 and Future Urban Electric Aircraft [NTRS: 20205004497]
  - NASA X-57 Cruise Motor Controller Airworthiness Test Approach [NTRS: 20205002485]
  - X-57 Cockpit Display System Development and Features [NTRS: 20230005312]
  - X-57 Cruise Motor Controller Design and Testing [NTRS: 20230006883]
  - X-57 Maxwell Aircraft EMI/EMC Integration Lessons Learned [NTRS: 20230008749]
- Subproject Documents (some are being proactively released, others may be available upon request and subsequent review)
  - REQ-CEPT-004, Power and Command Subsystem Requirements
  - SPEC-CEPT-001, Motor and Controller Specification
  - SPEC-CEPT-002, Traction Battery Specification
  - ICD-CEPT-002, Electrical Interface Control Document
  - ICD-CEPT-005, Command Bus ICD
  - ANLYS-CEPT-004, Cruise Motor Structural Analysis
  - REP-CEPT-002, Traction Bus Wire EMI/EMC Test Report
  - REQ-CEPT-026, Cruise Motor Controller (CMC) Requirements
  - REQ-CEPT-016, Battery Control Module (BCM) Requirements
  - REQ-CEPT-033, Traction Contactor Assembly (TCA) Hardware Requirements
  - REQ-CEPT-023, Cockpit Display System (CDS) Software Requirements
  - TP-CEPT-015, Cruise Motor (CM) Test Plan
  - TP-CEPT-013, XM3 Cruise Motor Controller (CMC) Test Plan
  - DOC-20423, Battery System User's Manual and Safety Instructions

[NTRS: «DocID»] → https://ntrs.nasa.gov/citations/«DocID»

Cockpit Displays

Papers

- X-57 Cockpit Display System Development and Features; Adam Curry, AFRC; (April 2023) Sean Clarke AFRC; Aamond Samuel, AFRC
- X-57 Power and Command System Design (May 2017), Clarke, Sean; Redifer, Matthew; Papathakis, Kurt; Samuel, Aamod; Foster, Trevor

X-57 Documents

- X-57 Power Pilot's Checklist; PCL-CEPT-019 (available upon request)
- Vehicle Subsystem Requirements; REQ-CEPT-001
- Power and Command Subsystem Requirements; REQ-CEPT-004
- Battery Control Module Requirements; REQ-CEPT-016
- Standby Cockpit Instruments Requirements; REQ-CEPT-032
- Cockpit ICD; ICD-SEPT-006
- Mod II Avionics Power Analysis; ANLYS-CEPT-020
- Mod IV Avionics Power Analysis; ANLYS-CEPT-032

CMC Documentation

- SPEC-CEPT-001 X-57 Cruise Motor and Controller Specification
- TP-CEPT-013 XM3 Cruise Motor Controller Test Plan
- PROC-CEPT-152 57CMC2001 XM3 CMC Assembly Process
- NASA X-57 Cruise Motor Controller Airworthiness Test Approach
- X-57 Cruise Motor Controller Design and Testing
- X-57 Propulsion System Airworthiness Acceptance Test Program Technical Memorandum

X-57 Performance and Sizing

Gray text indicates X-57-related publications but not official project publications

- M. D. Moore et al., "High-Speed Mobility through On-Demand Aviation," AIAA-2013-4373, August 2013
- A. M. Stoll et al., "Drag Reduction through Distributed Electric Propulsion," AIAA- 2014-2851, June 2014
- N. K. Borer, M. D. Moore, A. R. Turnbull, "Tradespace Exploration of Distributed Propulsors for Advanced On-Demand Mobility Concepts," AIAA-2014-2850, June 2014
- M. D. Patterson, *Conceptual Design of High-Lift Propeller Systems for Small Electric Aircraft*, Ph.D. thesis, Georgia Institute of Technology, May 2016
- N. K. Borer et al., "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator," AIAA-2016-3920, June 2016
- M. D. Patterson, J. M. Derlaga, N. K. Borer, "High-Lift Propeller System Configuration Selection for NASA's SCEPTOR Distributed Electric Propulsion Flight Demonstrator," AIAA-2016-3922, June 2016
- A. Dubois et al., "Design of an Electric Propulsion System for SCEPTOR's Outboard Nacelle," AIAA-2016-3925, June 2016
- N. K. Borer et al., "Comparison of Aero-Propulsive Predictions for Distributed Propulsion Configurations," AIAA-2017-0209, January 2017
- J. C. Chin, S. L. Schnulo, A. D. Smith, "Transient Thermal Analyses of Passive Systems on SCEPTOR X-57," AIAA-2017-3784, June 2017
- S. L. Schnulo et al., "Development of a Multi-Phase Mission Planning Tool for NASA X-57 Maxwell," AIAA-2018-3738, June 2018
- N. K. Borer, "Catalyzing Disruptive Mobility Opportunities through Transformational Aviation Power," AIAA-2018-3356, June 2018
- N. K. Borer, S. C. Geuther, B. L. Litherland, L. Kohlman, "Design and Performance of a Hybrid-Electric Fuel Cell Flight Demonstration Concept," AIAA-2018-3357, June 2018
- J. C. Chin, T. T. Tallerico, A. D. Smith, "X-57 Mod 2 Motor Thermal Analysis," AIAA-2018-3410, June 2018
- N. K. Borer, D. E. Cox, R. D. Wallace, "Flight Performance Maneuver Planning for NASA's X-57 "Maxwell" Flight Demonstrator – Part 1: Power-Off Glides," AIAA-2019-2855, June 2019
- S. L. Schnulo, D. Hall, J. C. Chin, "Further Development of the NASA X-57 Maxwell Mission Planning Tool for Mods II, III, and IV," AIAA-2019-4491, August 2019.
- J. C. Chin et al, "Battery Evaluation Profiles for X-57 and Future Urban Electric Aircraft," AIAA-202-3567, August 2020
- N. K. Borer, T. Bui, A. Smith, "Cruise Propulsion System Thermal Analysis for NASA's X-57 "Maxwell" Mod II Configuration," AIAA-2023-4273, June 2023
- J. M. Wilhite, N. K. Borer, M. A. Frederick, "Thermal Environments and Margin Guidelines for NASA's X-57 "Maxwell" Flight Demonstrator," AIAA-2024-1475, January 2024

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- M. D. Moore et al., "High-Speed Mobility through On-Demand Aviation," AIAA-2013-4373, August 2013
- M. D. Patterson, M. J. Daskilewicz, B. J. German, "Conceptual Design of Electric Aircraft with Distributed Propellers: Multidisciplinary Analysis Needs and Aerodynamic Modeling Development," AIAA-2014-0534, January 2014
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- N. K. Borer, M. D. Moore, A. R. Turnbull, "Tradespace Exploration of Distributed Propulsors for Advanced On-Demand Mobility Concepts," AIAA-2014-2850, June 2014
- M. D. Patterson, B. J. German, "Wing Aerodynamic Analysis Incorporating One-Way Interaction with Distributed Propellers," AIAA-2014-2852, June 2014
- N. K. Borer, M. D. Moore, "Integrated Propeller-Wing Design Exploration for Distributed Propulsion Concepts," AIAA-2015-1672, January 2015
- M. D. Patterson, M. J. Daskilewicz, B. J. German, "Simplified Aerodynamics Models to Predict the Effects of Upstream Propellers on Wing Lift," AIAA-2015-1673, January 2015
- M. Patterson, N. Borer, B. German, "A Simple Method for High-Lift Propeller Conceptual Design," AIAA 2016-0770, January 2016
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- N. K. Borer et al., "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator," AIAA-2016-3920, June 2016

X-57 High-Lift Propeller System (Continued)

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- M. D. Patterson, J. M. Derlaga, N. K. Borer, "High-Lift Propeller System Configuration Selection for NASA's SCEPTOR Distributed Electric Propulsion Flight Demonstrator," AIAA-2016-3922, June 2016
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- M. D. Patterson, N. K. Borer, "Approach Considerations in Aircraft with High-Lift Propeller Systems," AIAA-2017-3782, June 2017
- X. Fei, B. J. German, M. D. Patterson, "Exploring the Effects of Installation Geometry in High-Lift Propeller Systems," AIAA 2018-0277, January 2018.
- B. L. Litherland, J. M. Derlaga, "A Performance Analysis of Folding Conformal Propeller Blade Designs," AIAA-2019-3676, June 2019
- N. K. Borer, M.D. Patterson, "X-57 High-Lift Propeller Control Schedule Development," AIAA-2020-3091, June 2020
- B. L. Litherland, N. K. Borer, N. S. Zawodny, "X-57 "Maxwell" High-Lift Propeller Testing and Model Development," AIAA-2021-3193, August 2021
- B. Litherland, N. Borer, N. Zawodny, Z. Frederick "X-57 "Maxwell" High-Lift Propeller Test for Improved Thrust Measurements and Slipstream Velocities," AIAA, June 2022

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- Wallace, R., “Development of the Mod II X-57 Piloted Simulator and Flying Qualities Predictions”, AIAA 2023-4034, June 2023.
- Wallace, R., “Development of the Mod III/IV X-57 Piloted Simulator and Flighting Qualities Predictions”, AIAA TBD, July 2024.
- Wallace, R., “Mitigation of High Lateral Asymmetry Rates Due to Loss of Cruise Motor on Mod III X-57”, AIAA TBD, July 2024.
- Reynolds J., “Human Machine Interaction with a Research Electric System on the X-57 Aircraft”, AIAA TBD, July 2024.
- Chin, J. “Battery Performance Modeling on SCEPTOR X-57 Subject to Thermal and Transient Considerations”, AIAA 2019-0784, January 2019.
- McMinn, J., “ANLYS-CEPT-035 X-57 CG Trim and Take-off Rotation Study”, NASA TM TBD.
- Reynolds J., “PLAN-CEPT-022 Pilot Simulation Training Plan”, NASA TM TBD.

High-Lift Motor Controller

- Garrett, M., et al. “Development of an 11 kW lightweight, high efficiency motor controller for NASA X-57 Distributed Electric Propulsion using SiC MOSFET Switches,” 2019 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), IEEE, 2019, pp. 1–8
- Maroli, J. M., et al. “Utilizing Code Generation from Models for Electric Aircraft Motor Controller Flight Software,” *AIAA AVIATION 2023 Forum*, 2023, p. 4274.
- Pending publication: Kowalewski, S., et al. “NASA’s X-57 High-Lift Motor Controller: Detailed Design, Test Results, and Outcomes” *AIAA AVIATION 2024 Forum,* 2024
  - Publication will include HLMC RevH schematics with part information and layout images

System Safety

- Burkhardt, P., “X-57 Hazard Development Approach”, AIAA Aviation 2024 Paper (to be published)
- X-57 System Safety Plan (Ref. SSP-CEPT-002_Rev. B)
- X-57 Hazards, i.e., Mod II – IV Flight and Mod II Ground Operations (PSFT/HVT).pptx
- X-57 Hazards, i.e., Mod II Flight and Mod II Ground Operations (PSFT/HVT), Long Forms.pdf
- X-57 Hazards, i.e., Airvolt CMET, Long Forms.pdf

System Integration & Test

- McLaughlin, K., Vidyasagar, R., Lucht, J., Waddell, A., Rudy, J., Curry, A.F., “X-57 Flight Systems Integration Path”, AIAA Aviation 2024 Paper (to be published)
- Waddell, A., McLaughlin, K., “X-57 Battery Systems Lessons Learned,” AIAA Aviation 2024 Paper (to be published)

Mission Planning

- Publicly Available
  - Mod II Mission Operations Plan (MOP) OPS-CEPT-002
  - Mod II Go/No-Go Parameter List - OPS-CEPT-001
  - Operational Flight Envelope – TP-CEPT-010
  - Mod II Airspeeds – OPS-CEPT-006
- Soon to Be Released
  - AIAA Conference Paper on the X-57 Flight Test Plan
- Available Upon Request
  - Pilot's Checklist – PCL-CEPT-019
  - Mod II Flight Test Plan (FTP) - FTP-CEPT-005

Design Criteria, Requirements and Reports (Publicly Available)

- NASA AFRC Aircraft Structural Safety of Flight Guidelines, AFG-7123.1-001
- REQ-CEPT-006 - Structural Loads Requirements for High-Lift Structure
- REQ-CEPT-007 - Structural Loads Requirements for Floor and Equipment Support
- REQ-CEPT-008 - Structural Loads Requirements for Mod II Wing Motor Mounts
- REQ-CEPT-010 - Structural Loads Requirements for Cruise Motor
- REQ-CEPT-015 - Structural Loads Requirements Loads Analysis for Mod III Cruise Nacelle Structure
- SPEC-CEPT-003 Rev A - Mod III/IV Wing Structural Specifications
- SPEC-CEPT-004 - High-lift Propeller Specification
- ANLYS-CEPT-007 (Rev B) - Landing Gear and Mod II Wing Loads Analysis
- ANLYS-CEPT-021 - X57 SCEPTOR Fuselage Structural Analysis
- Mod III Wing Loads Analysis Report (Pending Release)
- Mod III Wing Stress Analysis Report (Pending Release)
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Static Structures

- Miller, et al. X-57 Wing Structural Load Testing, AIAA 2020-3090, 2020
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- *Whirl Flutter and the Development of the NASA X-57 Maxwell*, (IFASD 2019) -- https://ntrs.nasa.gov/citations/20200002633
- *All-Electric X-Plane, X-57 Mod II Ground Vibration Test,* (SEM IMAC 2020 paper) -- https://ntrs.nasa.gov/citations/20205006955
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- Mod II/III/IV Flutter Analysis (AIAA AVIATION 2024)
- Electric Motor Vibrations Measured on NASA X-57 Maxwell Aircraft (AIAA AVIATION 2024)
- Mod III Wing GVT (SEM IMAC 2025)