National Aeronautics and Space Administration

ARMD Transformative Aeronautics Concepts Program

LEAPTech/HEIST Experiment Test and Evaluation Lessons Learned

26 June 2018

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Code 520 – Aerodynamics and Propulsion
661-276-2620

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Introduction

- **Leading Edge Asynchronous Propeller Technology (LEAPTech)**
- **Hybrid-Electric Integrated Systems Testbed (HEIST)**
- **LEAPTech was the first experiment of the HEIST project**
- **The LEAPTech/HEIST experiment was a joint effort between**
  - NASA Langley
  - National Aeronautics and Space Administration (NASA) Armstrong
  - Joby Aviation Inc. (Joby)
  - Empirical Systems Aerospace (ESAero)
- **Project began in the NARI/Seedling project and transferred to CAS which replaced the NARI/Seedling project.**
- **Project transferred to Convergent Aeronautics Solutions (CAS)**
  - Under the Transformative Aeronautics Concepts Program (TACP) in 2014
  - Concentrates on sharply focused studies
  - Program provides flexibility to assess new-technology feasibility

Background

- First experiment of the Hybrid-Electric Integrated Systems Testbed (HEIST) project.
- Included design, analysis and slow speed truck testing
- Fast paced program that lasted a total of 24 months from start to finish
- Identify possible advancements through optimized propulsion airframe integration, distributed electric motors, wing design, propeller design, as well as various other disciplines
- Demonstrate radical improvement in lift

Background Continued

♦ LEAPTech Test Article Description

- Experimental setup was designed to both streamline construction and to deliver useful data/analysis
- Detailed specification is presented by Stoll[1].
- Steel wing support structure:
  - Suspended with airbags, to isolate the support structure from road vibrations.
  - Large water tanks mounted below the airbags to lower the center of mass.
  - Sway braces constrain airbag lateral displacement.
- Wing:
  - Center section is a straight wing section, primary wing sections had constant linear taper, sweep, and twist.
  - Eighteen evenly spaced Joby JM1 brushless electric motors
  - Fowler flaps along span except at root unswept section
  - Configured to manually be set at 0 ,10, 20, 30 or 40 degrees.

Testing Summary

- **Blown and Unblown data collected at various wing angles of attack and fap setting at 40 degrees**
  - Data Indicates improved lift on a blown wing configuration
- **Motor Power data collected at various wing angles of attack and fap settings of 10, 30 and 40 degrees**
  - Data Indicates a discrepancy between the left-turning and right-turning propellers

- **Issues preventing full success – Lessons Learned items**
  - System Design
  - System Maintainability
  - Propeller design
  - Aerodynamic assumptions
  - Test Condition Uncertainty

Lessons Learned Approach

- **Lessons arranged in a chart form with the headings below**
  - Lesson
    - Lesson Description and Identifier if applicable
      - Example: Difficult Instrumentation maintainability 1
  - Problem/Success
    - Problem Summary
    - Or Success Summary
  - Impact
    - The identified impact of the Problem or Success
    - Summarized
  - Recommendation
    - The Identified Recommendation based on the test and requirement

Lesson	Problem/Success	Impact	Recommendation

Lessons Learned

Lesson	Problem	Impact	Recommendation
Difficult Instrumentation maintainability	**Force balance system was over-constrained**	**Precise rebalancing of the load cells each time the wing configuration was changed** and throughout test sessions due to thermal loading	Incorporate instrumentation design early in the design process while test article interfaces and allowances can be modified
CAN network integration	**Single-bus CAN network evidenced grounding and noise problems during integrations**	The **CAN bus would often report a loss of communication and switch to a self-shutdown mode** when the motor controllers were running at high power	Expect integration challenges. "Grounding" is challenging on vehicles and more so when there are several power buses with EMI or ground loops possible.
Complete all integration in a total design	**Instrumentation system was designed independently of the traction propulsion system**	**Imposed a separate daily battery charging and monitoring requirement** on the test team	Include concept of operations early in the development process. Consider major subsystems to manage maintainability. Integrate power to provide for all operations
CFD Missed Key items of interest	**CFD Analysis Requirements were not sufficient**	**Test Assumptions and setup were incorrect**	CFD expertise is not just for the design, but needed also to model the actual day of test conditions

Lessons Learned Continued

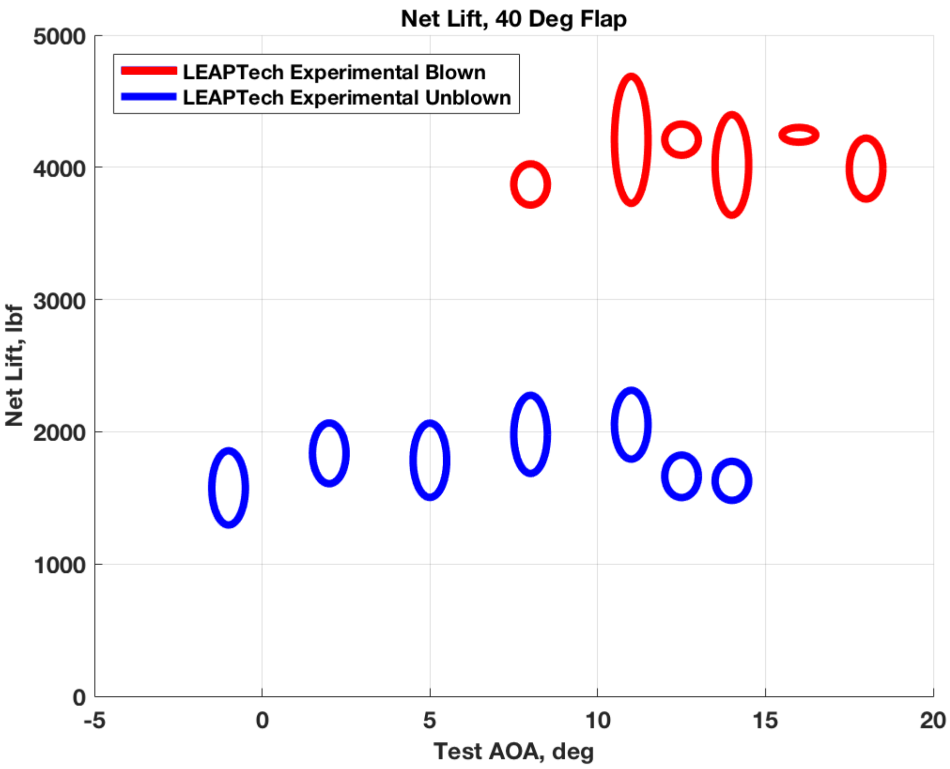
Lesson	Problem	Impact	Recommendation
Reduced propeller maintainability	Over the lifecycle of the test program the showed **evidence of bending at the propeller roots and of failure of the circumferential bonds**	This **required significant investigation and increased the inspection** frequency of the propellers considerably.	Future applications of blown lift augmentation with electric propulsion could avoid motor power loss of performance by designing more robust propellers
Aerodynamics	**On a "good" test day, it was observed +1 to +2 deg beta AND -2 to -3 degree alpha on the same runway pass (~1 minute apart)**	**73 mph +/- 3 knots headwind yields +/- 9.7% in qbar** and 73 mph +/- 3 knots crosswind yields +/- 3.5 deg beta	Measure the freestream test conditions at the test article
Quantify Uncertainty using CFD	**CFD Analysis did not account for uncertainty**	**Attempts to understand sources of error were unsuccessful**	Identify pre-test limits such as max allowable crosswind limits, airspeed tolerances, vehicle velocity tolerances, etc. or quantify effect post test
Thrust System Asymmetry	**Motors on left wing are absorbing about 15% more power than those on right wing**	Yawing moment created by **thrust imbalance as much as 300-400 ft-lbf**	Verify thrust system assumptions before testing or scope project to quantify uncertainty

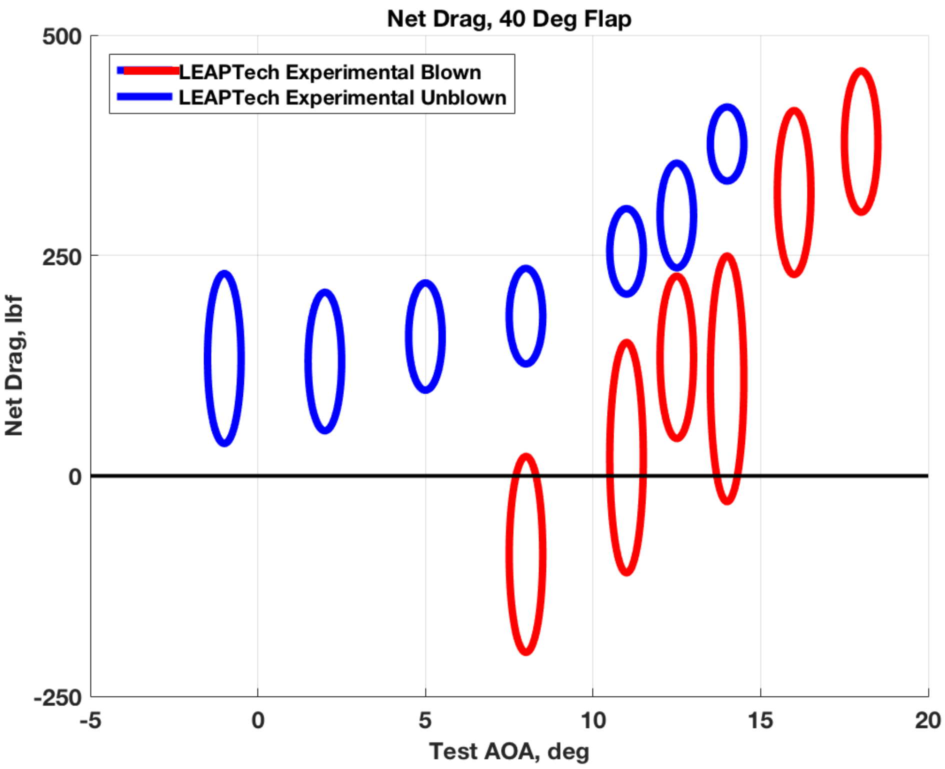
Aerodynamic Uncertainty Contributions

- **LEAPTech Known Factors of Uncertainty**
  - Angle of Attack
  - Data time sync between all sets of data
  - Lift / Pitch / Roll Load Cells (4 each -- overconstrained)
  - Accurately measure the test condition
  - Low Speed 73 MPH test condition:
    - +/- 3 knots headwind yields +/- 9.7% in dynamic pressure
    - +/- 3 knots crosswind yields +/- 3.5 deg beta
- **Unknown Factors**
  - Dynamic Pressure uncertainty and components
    - Static Pressure uncertainty
  - Thrust Asymmetry Uncertainty due to:
    - Inconstant Right and Left propeller design
    - Possible power delivery inconsistencies
  - Mystery Structural Mode observed in load cell data

Aerodynamic Test Results and Uncertainty

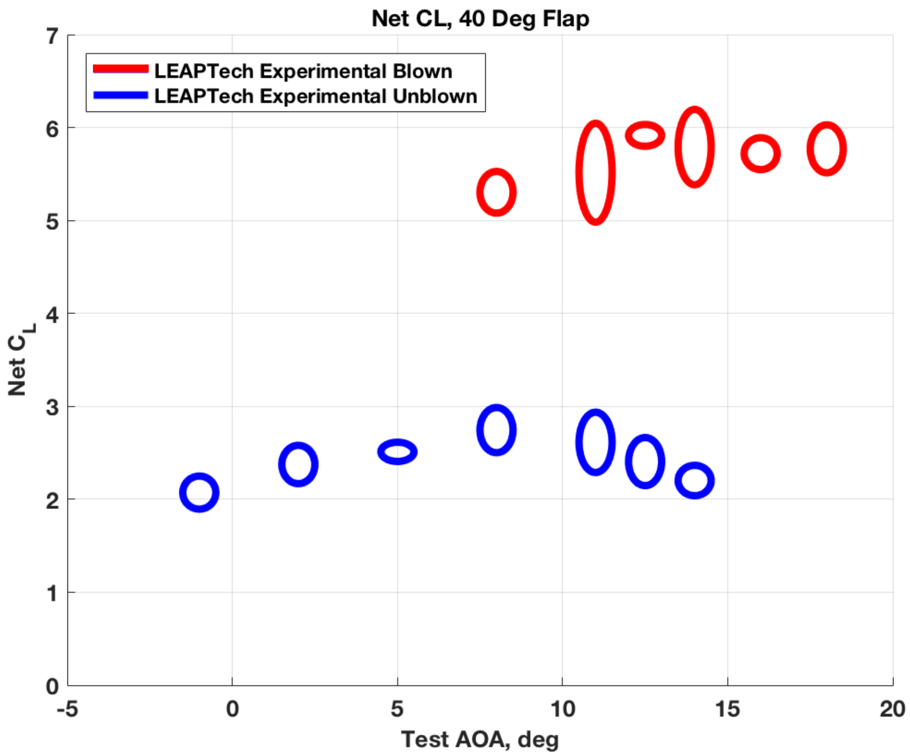
Net Lift and Drag and Uncertainty
Blown Wing (Props Powered) & Unblown Wing

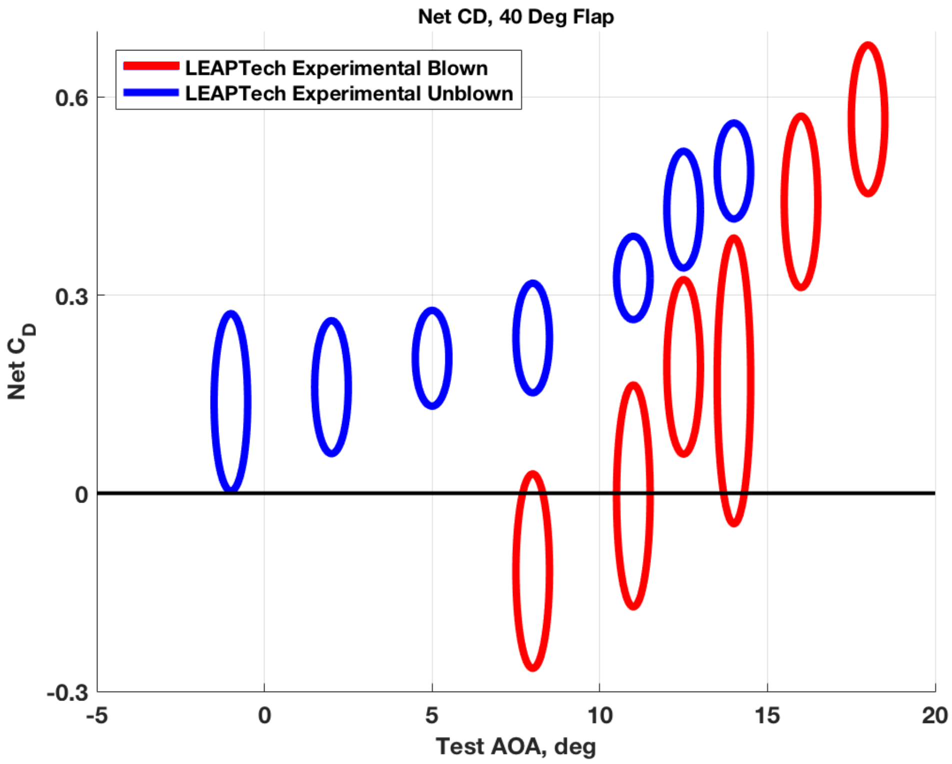




Aerodynamic Test Results and Uncertainty

Net C_L and C_D and Uncertainty
Blown Wing (Props Powered) & Unblown Wing





Motor Power Uncertainty Contributions

- **Known Factors of Uncertainty**
  - Propeller cracking
    - Varying levels between blades and between props
    - Along leading edge of the blades - leading to different loading profiles
  - Non-uniform heating/cooling spanwise down the wing
    - Instrumentation and structural choke points along the full span
  - Each motor was handmade with unique performance characteristics
  - Flow interference from the truck and the struts affected the inboard motor/propeller (propulsor) flow more than the outboard propulsors
  - Communication intermittency with specific motors
- **Unknown Factors**
  - Disparity in power consumption between starboard and port motors
  - Throwing magnets possibly caused by environmental dust/salt air from lakebed, propellers out of balance, high vibration environment, thermal stress and magnet adhesive.

Motor Power Test Results and Uncertainty

Wing Settings		Average Power Values for Both Runs [kW]																		
Wing Angle	Flap Angle	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Total Power [kW] 6860 RPM
13.5	40	13.2	11.6	13.6	12.4	13.0	13.5	13.2	12.2	12.9	9.5	11.1	12.7	10.7	11.8	10.3	10.7	10.4	11.3	214.0
19	40	13.7	12.0	14.1	12.8	13.6	13.8	13.6	12.8	13.6	9.8	11.3	12.9	11.1	12.7	10.9	11.1	11.0	11.7	222.7
17	40	13.5	11.9	14.0	12.7	13.3	13.8	13.3	11.4	12.7	9.6	11.4	12.4	10.8	12.1	10.5	11.0	10.5	11.3	216.3
9	10	12.7	11.1	13.0	11.7	12.4	12.7	12.5	11.8	12.5	9.3	10.6	11.9	10.1	11.6	10.0	10.1	10.1	10.9	205.0
12	10	13.1	11.4	13.3	10.0	12.7	13.1	12.8	12.0	12.8	9.4	10.8	12.2	10.4	11.8	10.1	10.3	10.2	11.1	207.7
15	30	13.2	11.6	13.7	12.3	13.1	13.5	13.2	12.2	12.7	9.5	11.1	12.5	10.6	11.9	10.3	10.7	10.3	11.2	213.8
15	40	13.3	11.7	13.8	12.4	13.1	13.5	13.3	12.4	13.1	9.8	11.1	12.5	10.8	12.4	10.6	10.7	10.6	11.4	216.6
9	40	12.9	11.4	13.4	12.0	12.9	13.2	12.8	12.1	12.7	9.5	10.8	12.2	10.4	11.8	10.2	10.4	10.2	11.2	210.1
12	40	13.4	11.7	13.9	12.4	13.2	13.7	13.3	12.4	13.2	9.8	11.2	12.7	10.8	12.0	10.4	10.7	10.4	11.4	216.6
12	30	12.9	11.3	13.2	11.9	12.6	12.9	12.7	11.9	12.6	9.4	10.7	12.1	10.4	11.8	10.0	10.3	10.2	10.9	207.8
6	30	12.7	11.1	12.9	11.6	12.4	12.7	12.5	11.9	12.6	9.4	10.2	11.9	10.2	11.6	10.0	10.1	10.1	10.9	204.7
9	30	14.0	12.7	14.5	12.9	13.9	14.1	13.8	13.0	13.9	10.7	11.5	13.1	11.6	13.4	11.4	11.3	11.5	12.4	229.7
6	40	12.5	11.2	13.1	11.6	12.5	12.8	12.5	11.9	12.6	9.5	10.4	11.8	10.3	11.8	10.1	10.1	10.2	11.0	205.8
9	40	13.9	12.6	15.4	12.8	14.5	14.1	13.8	13.6	13.7	11.3	11.9	13.0	11.5	12.7	11.5	11.6	11.1	12.0	231.0

9-9.9	10-10.9	11-11.9	12-12.9	13-13.9	14-14.9	15-15.9

Process Improvement Recommendations

- The role of the Principal Investigator on a small research effort includes many responsibilities such as concept designer, Chief Engineer and Project Manager. It is a good learning opportunity but an external network of experts to provide mentorship and advice is still needed. If resources are available it would be better for the PM and Chief engineer role to be supported by others.
- There must be a balance in the time spent designing the experiment and testing. Too much time spent on perfecting the CFD left little time for integrating and troubleshooting the test results. Also the small changes being made in CFD design could not be measured in the test setup.
- Using small businesses to have more agility in processes, purchasing and testing saves time, but make sure you plan to add time into fabrication quality requirements

Conclusions

Experiment

- The LEAPTech experiment data showed improved lift with a flap setting of 40 degrees for the unblown and blown configurations and verified feasibility.
- Gaps in Motor Controller technologies were understood and new requirements were passed to industry and NASA GRC, to develop new advancements in motor controllers designed for aircraft applications. As a result, GRC designed new High Lift motor controllers for the X-57 project
- Sub-contractors for the motors learned lessons on quality assurance which helped the reliability in the X-57 Cruise Motors

Conclusions Continued

Lessons Learned

- The volume needed for wiring in the wing informed the X-57 wing design that a lower aspect ratio would be needed to fit everything in the wing
- The causes of EMI were better understood and fed into a new wiring scheme for X-57
- When a testbed capability also becomes the experiment in which to test the actual experiment, there be more troubleshooting and uncertainty in your data
- Teams with members located at different research centers need time to build trust and integrate. The result is a strong team with the right complementary competencies

Questions?

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References

[1]Alex M. Stoll. "Comparison of CFD and Experimental Results of the LEAPTech Distributed Electric Propulsion Blown Wing", 15th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, (AIAA 2015-3188)

[2] Murry, J., Lechniak, J. A., "The LEAPTech Experiment, Approach, Results, Recommendations", Oct 20, 2016, DFRC-E-DAA-TN36158.

[3] https://www.nasa.gov/aeroresearch/programs/tacp

Lessons Learned

Lesson	Problem/Success	Impact	Recommendation
Difficult Instrumentation maintainability 1	Force balance system was over-constrained	Precise rebalancing of the load cells each time the wing configuration was changed and throughout test sessions due to thermal loading over time	Incorporate instrumentation design early in the design process while test article interfaces and allowances can be modified
Difficult Instrumentation maintainability 2	Each motor was volumetrically constrained	Temperature sensors limited the design to crimped connections and specialized tooling was required to re-integrate wiring.	Incorporate maintainability and handling requirements up front. Include clean disconnect points between components
Complete all integration in a total design 1	Instrumentation system was designed independently of the traction propulsion system	Imposed a separate daily battery charging and monitoring requirement on the test team	Include concept of operations early in the development process. Consider major subsystems to manage maintainability. Integrate power to provide for all operations
Complete all integration in a total design 2	Each motor had a dedicated DC traction bus (pair of conductors) and separate low-voltage logic power	The system proved to be very reliable, but this also increased operations and maintenance overhead because of the large number of connections	Include value consideration of simple design architectures (more reliable) vs. robust architecture (easy to operate).

Lessons Learned Continued

Lesson	Problem/Success	Impact	Recommendation
The battery system charging	The battery configured was six independent series-string of cells which complicated the design and the interface between the chargers and the batteries	Several of the $LiFePO_4$ cells failed during the operation	Consider integration, storage, and operating environment in the design phase and bookkeep additional spare parts or additional handling controls if failure risk is credible
CAN network integration	Single-bus CAN network evidenced grounding and noise problems during integrations	The CAN bus would often report a loss of communication and switch to a self-shutdown mode when the motor controllers were running at high power	Expect integration challenges. "Grounding" is challenging on vehicles and more so when there are several power buses with EMI or ground loops possible. Set aside time to integrate and iterate complex control systems
Traction hardware challenges	A 16.8 kW motor controller that was selected for design but was under powered for the required testing	A larger motor controller system rated at 33.6 kW which was implemented but could not be accommodated within the nacelle volume	Verify and test potential components before hardware is designed around the components

LEAPTech/HEIST Experiment Lessons Learned

Lessons Learned Continued

Lesson	Problem/Success	Impact	Recommendation
Reduced propeller maintainability	Over the lifecycle of the test program the painted surface finish was observed to show evidence of bending at the propeller roots and of failure of the circumferential bonds	This required significant investigation and increased the inspection frequency of the propellers considerably.	Future applications of blown lift augmentation with electric propulsion could avoid motor power loss of performance by designing more robust propellers
CFD Missed Key items of interest	CFD Analysis Requirements were not sufficient	Test Assumptions and setup were incorrect	CFD expertise is not just for the design, but needed also to model the actual day of test conditions
Quantify Uncertainty using CFD	CFD Analysis did not account for uncertainty	Attempts to understand sources of error were unsuccessful	Identify pre-test limits such as max allowable crosswind limits, airspeed tolerances, vehicle velocity tolerances, etc. or quantify effect post test
Thrust System Asymmetry	Motors on left wing are absorbing about 15% more power than those on right wing	Yawing moment created by thrust imbalance was about 300-400 ft-lbf	Verify thrust system assumptions before testing or scope project to quantify uncertainty

Lessons Learned Continued

Lesson	Problem/Success	Impact	Recommendation
Instrumentation measurement uncertainty	Sources of uncertainty in measurements could have been improved regarding vehicle speed and air data.	Measurement uncertainty reduced confidence in the data and quantification of key classical parameters	Air data probe placed closer to free stream conditions away from local effects of the truck and propulsion disturbances.
Structural Dynamics	Multiple structural modes present, some likely with significant nonlinearities	Introduced uncertainty that was not quantified due to project scope	Verify structural dynamics assumptions are correct before testing or scope project to quantify uncertainty
Aerodynamics 1	“Blowing” changes the effective dynamic pressure	Blowing the wing significantly decouples the local aero from the freestream conditions	Comparison of Lift and Drag may be more meaningful than CL and CD
Aerodynamics 2	On a “good” test day, it was observed +1 to +2 deg beta AND -2 to -3 degree alpha on the same runway pass (~1 minute apart)	73 mph +/- 3 knots headwind yields +/- 9.7% in qbar and 73 mph +/- 3 knots crosswind yields +/- 3.5 deg beta	Measure the freestream test conditions at the test article