National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681

INTEROFFICE MEMORANDUM
LaRC-DFLY-0001

DATE: 17 May 2024

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SUBJECT: Completion of Dragonfly PPF Testing in the NFAC 80x120-Foot Wind Tunnel

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Introduction

The Dragonfly entry, descent, and landing team (JHU-APL, NASA Langley Research Center, NASA Ames Research Center, Sikorsky Aircraft) recently completed testing in the National Full-Scale Aerodynamics Complex (NFAC) 80x120-Foot Wind Tunnel. The facility is located at NASA Ames Research Center and is operated by the U.S. Air Force's Arnold Engineering Development Complex. The test was designed to simulate conditions of Preparation for Powered (PPF), an approximately 10-minute period during which the Lander is posed in front of the Backshell at low subsonic airspeeds, all under the main parachute, and the rotors are used to null residual Lander yaw rates prior to release i. e. de-spin (Figure 1). The Lander (approximately 50% scale) that previously was tested in the NASA Langley 14x22 Wind Tunnel in 2023 was used for the NFAC test with a new Backshell designed and fabricated specifically for NFAC. This memorandum summarizes execution of the test: objective, facility and models, instrumentation and data products, test procedure, and completed test matrix. Other future documents will include a test report (JHU-APL) and documentation of data processing/analysis and computational fluid dynamics (CFD) comparisons to test data (Sikorsky).

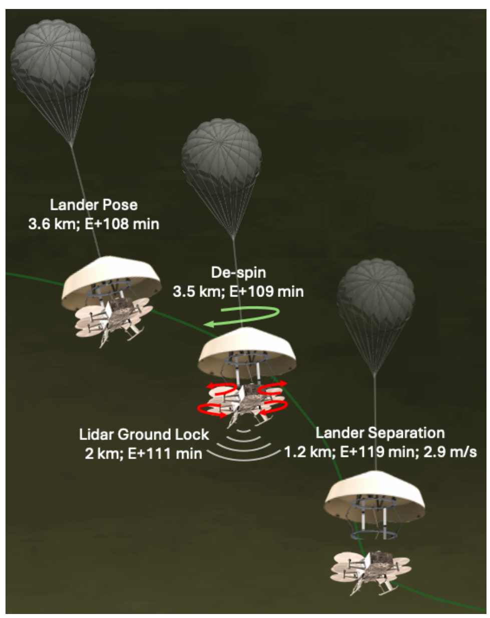


Figure 1 Preparation for Powered Flight

Test Objective

The primary test objective was to measure the combined aerodynamic/propulsive forces and moments from sting-mounted test articles, the primary one being the Lander (rotors, rotor arms, body) and a Backshell in simulated PPF conditions in the NFAC 80x120 tunnel. The Lander also was tested by itself prior to Backshell installation. Prior to the test, there existed no relevant low-speed ground test data of a powered Lander in front of the Backshell in vertical descent similar the

Dragonfly PPF configuration. The test data will not be directly applied to the Lander and Backshell in the Titan environment, but rather comparisons between test data and CFD results provided by Sikorsky will be used to calibrate the overall CFD analysis approach for the wind tunnel model at NFAC conditions. By extension, the quantitative comparisons between the CFD results and test data will be used to validate Sikorsky's CFD-based PPF aerodynamics model and uncertainties for Dragonfly at Titan conditions.

Test Facility

NFAC (Figure 2) is comprised of two rectangular test sections (40 feet high and 80 feet wide i. e. 40x80 and 80-by-120 feet) driven by a common six-fan system. The 80-by-120 facility is the world's largest wind tunnel and is capable of testing full-sized airplanes at airspeeds up to 100 knots. The 80-by-120 tunnel was used for Dragonfly testing due to its availability and its larger test section would reduce tunnel wall effects on data quality.

Figure 2 NFAC facility (left) and 80x120-foot test section with Dragonfly test article (right)

Model Configurations

Two model configurations were tested at NFAC: 1. The Lander by itself and 2. The Lander in the posed position with the Backshell. Two modifications were made to the Lander after 14x22 testing was completed to better approximate the Titan Lander: 1. A "cradle" through which the Titan Lander is attached to the pose mechanism and 2. Two vertical fins at the rear of the Lander. In the NFAC test, the Lander and Backshell were attached to separate internal force and moment balances, but were not attached to one another. Figure 3 shows the tested Lander and Backshell configuration compared to Dragonfly. The NFAC Lander and Dragonfly are geometrically different in some respects, but none of these differences were considered to be significant for the purposes of collecting test data at simulated PPF conditions. All geometric scaling for the test was based on the Titan Lander and Backshell configurations that were received from Lockheed Martin in May 2023. The Backshell diameter was scaled such that the rotor centers of the NFAC Lander were in the same relative radial position as they are for the Titan Lander. It was deemed important for the test that the rotors be placed such that the blade tip paths overlap the Backshell rim by the same amount, to simulate the same fluid dynamics phenomena. Since the NFAC Lander body and rotor arm geometries are not scale versions of the Titan Lander, this scaling approach resulted in a 58% scale Backshell. The tested Lander and Backshell were placed at the same fixed relative separation distance as they are in the Titan Lander's posed position. The Lander aerodynamic coordinate system and rotor numbers are shown in Figure 4. The PPF de-spin maneuver involves using pairs of lower rotors from opposite corners (e. g. 5 and 7 or 6 and 8) to generate a moment around the Lander Z axis (yaw) in the direction opposite from the detected yaw motion.

The original test matrix included testing of the Backshell alone at the end of the test campaign, to collect low-speed aerodynamics data for the Backshell after Lander separation. However, once the Lander and Lander-plus-Backshell test matrices eventually were completed, there was not enough time to remove the Lander and test the Backshell by itself.

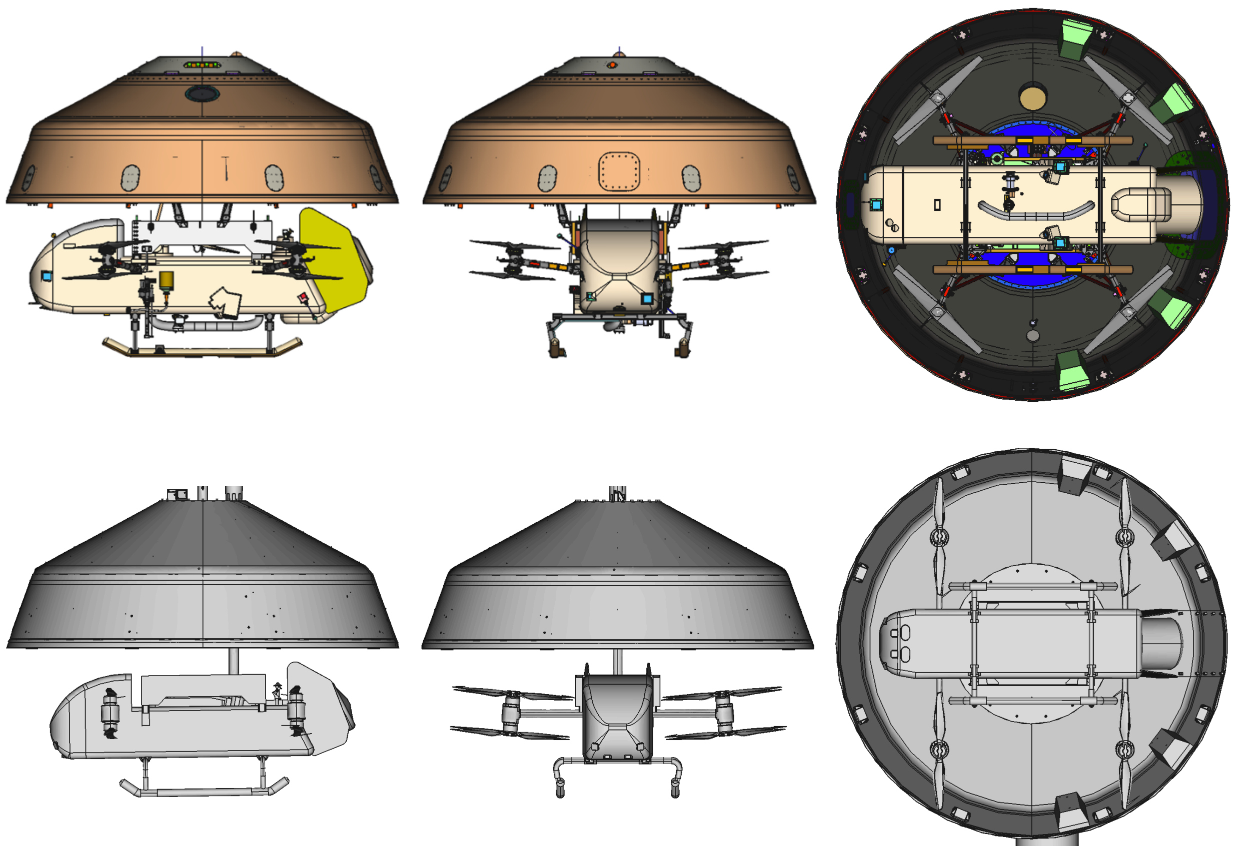


Figure 3 Titan Dragonfly in posed position (top) and NFAC Lander + Backshell configuration (bottom)

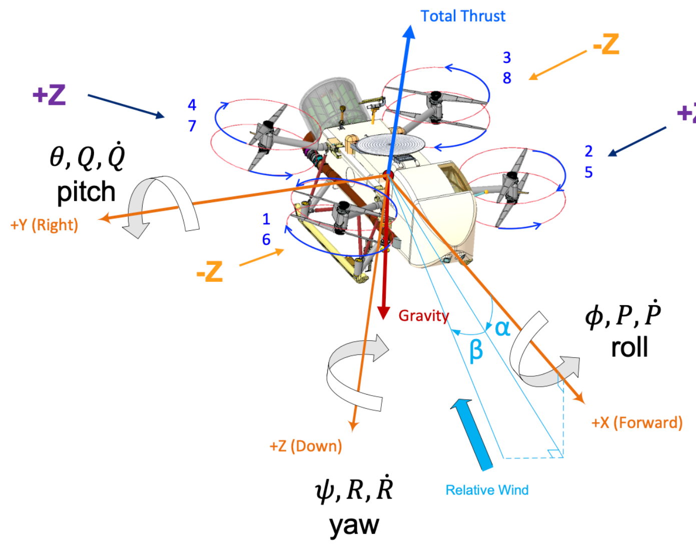


Figure 4 Lander aerodynamic coordinate system and rotor numbers

Figure 5 illustrates how the models were mounted in the NFAC test section. The Lander and Backshell had separate stings to accommodate two force and moment balances. The models were mounted with the left side of the Lander pointed towards the tunnel floor, an orientation that was also used for 14x22 testing. The models were approximately in the middle of the test section, both vertically and horizontally. Figure 6 shows pictures of the installed Lander and Backshell.

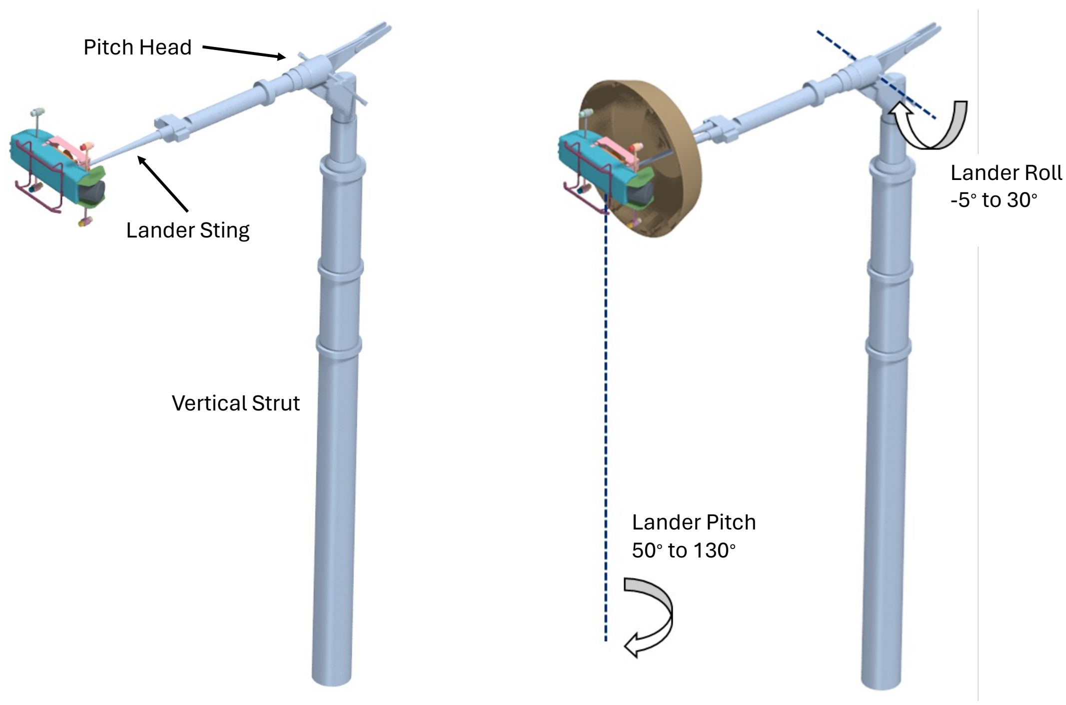


Figure 5 Model orientation for Lander (left, rotor blades not shown) and Lander + Backshell (right). Lander pitch and roll angles shown are 90 and 0 degrees, respectively. Image Credit: Kalki Sharma, Sikorsky.

Figure 6 Installed Lander and Backshell (left) and picture taken from downstream of model with test section inlet in background (right).

Instrumentation

In addition to the typical wind tunnel conditions (velocity magnitude, static density, static temperature, dynamic pressure, etc.), key parameters to be compared to CFD results from Sikorsky were supplied. The primary research data products supplied to the customer are listed in Table 1. NASA Langley provided balances for both the Lander and Backshell. The Lander balance previously was used for the 14x22 test. The Backshell balance was re-calibrated prior to NFAC testing. The same rotor load cells (Figure 7) that were used in the 14x22 tests also were used for NFAC testing. Electronically scanned pressure (ESP) modules were used to measure static pressure on the Lander (Figure 8) and Backshell (Figure 9). A total of 55 static pressure taps were placed on the Lander body identical to the 14x22 test arrangement. A total of 49 static pressure taps were placed on the Backshell skin, 17 on the outer surface and 32 on the inner. The taps measured the steady-state pressure that was used to calculate pressure coefficient. Three-component velocities upstream of test article were provided using four RM Young 81000 ultrasonic anemometers on each of two upstream towers (Figure 10). The airspeed measurements and uncertainties provided by NFAC were used by Sikorsky to estimate test data uncertainties.

Table 1 Primary instrumentation

Measurement	Instrument (Count)	Data Products
Six-component forces and moments from Lander body + rotors	NASA Langley balance LRC-716	Forces (3) and moments (3) in X/Y/Z directions
Six-component forces and moments from Backshell	NASA Langley balance 711B	Forces (3) and moments (3) in X/Y/Z directions
Six-component forces and moments from rotors 2, 3, 5, 8	ATI Delta load cells (4)	Forces (3) and moments (3) in X/Y/Z directions
Static pressure on the Lander body	ESP static pressure taps (55)	Pressure coefficient
Static pressure on the Backshell	ESP static pressure taps (49)	Pressure coefficient

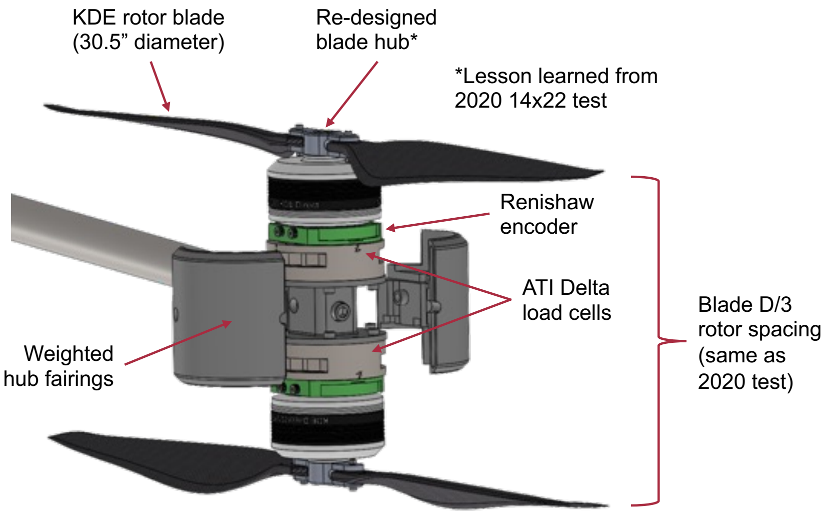


Figure 7 Coaxial rotor detail with 2 load cells

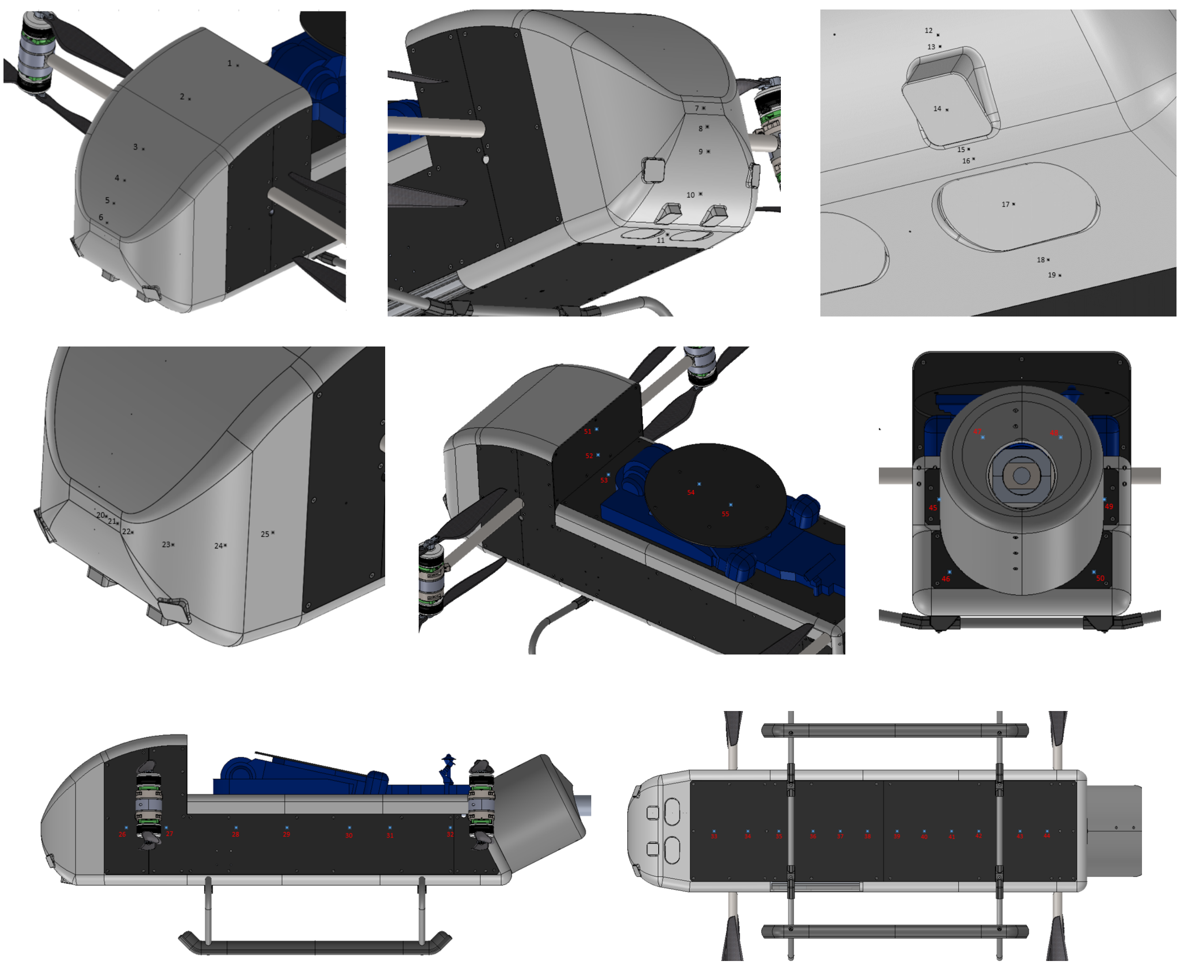


Figure 8 Static pressure taps on Lander (55 total taps)

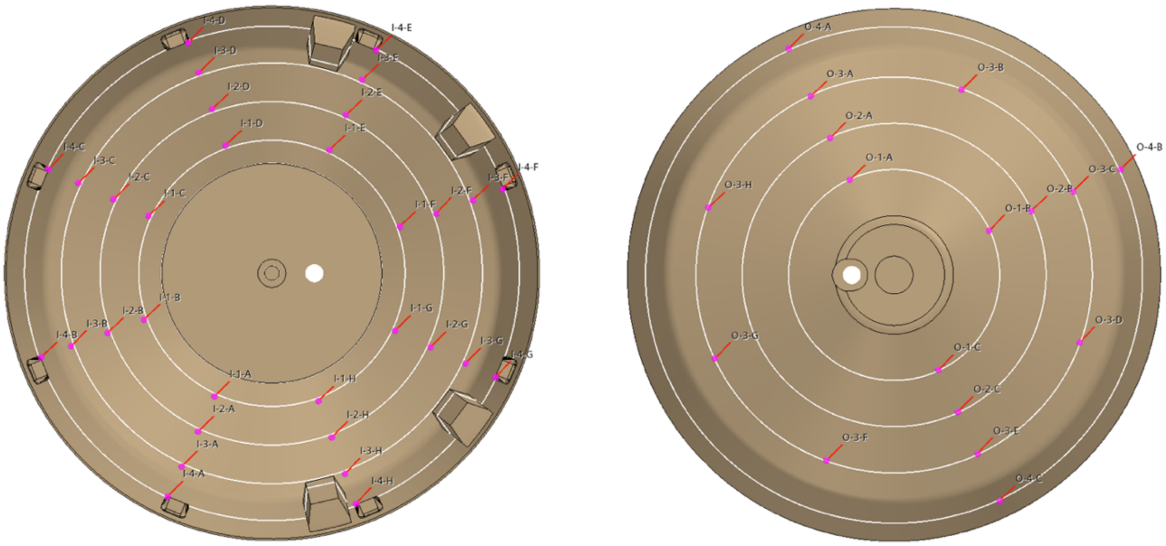


Figure 9 Static pressure taps on Backshell inner surface (left, 32 taps) and outer surface (right, 17 taps). Image credit: Kalki Sharma, Sikorsky.

Figure 10 Test section with two towers upstream of model, each equipped with 4 RM Young 81000 ultrasonic anemometers

Test Procedure

The test was conducted by a team from NFAC and all customer organizations. NFAC oversaw coordination of the test, operated and monitored the wind tunnel, controlled the NFAC data system, and assured data quality to meet customer requirements. The NFAC data system recorded all tunnel parameters, model attitude, data from both balances, and all static pressure tap data. The JHU-APL roles were focused on the JHU-APL data system and Lander: test lead, operator, data analyst, model engineer, and safety representative. The JHU-APL data system recorded the rotor load cell data (loads and temperatures) and all data related to the Lander operation (rotor RPM, rotor drive temperatures, motor current, etc.). NASA provided a test director to assure data quality and to determine test matrix priorities and adjustments to meet overall test requirements. Sikorsky Aircraft provided personnel and hardware for structural testing of the Lander and Backshell, on-site test data quality checks, preliminary data processing, and recommendations for test matrix adjustments. Post-test data processing, including merging of the NFAC and JHU-APL data system products, was completed by Sikorsky.

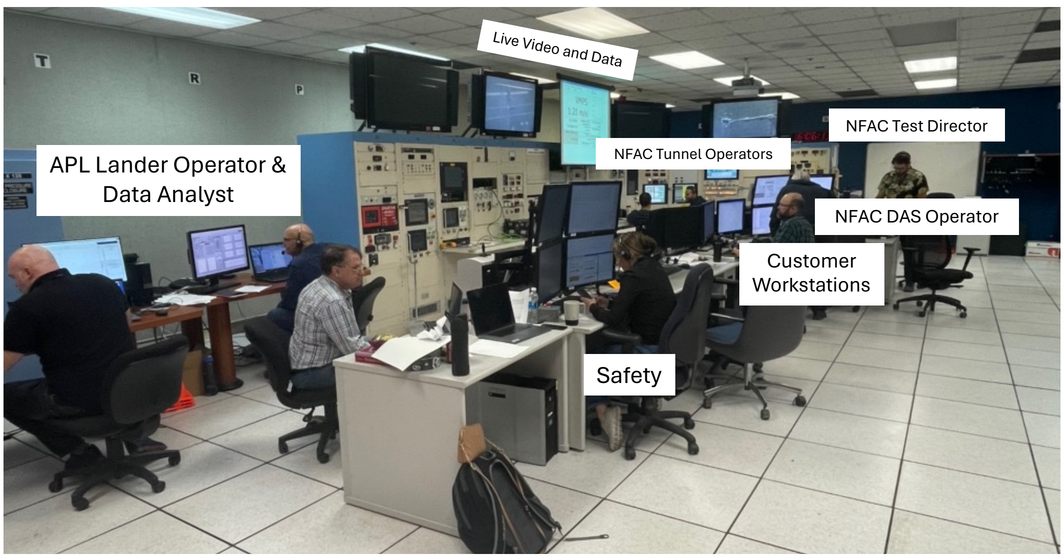


Figure 11 NFAC 80x120 control room

Each test point consisted of a specific tunnel test section speed, Lander pitch angle, Lander roll angle, and Lander rotor sequence. The rotor sequences are specific combinations of rotor RPM as described in Table 2. The baseline rotor sequences for Titan PPF de-spin at the time of testing were Q1 and Q7, which are intended to generate positive and negative Lander yaw moments, respectively. The other lower-priority rotor sequences were designed as alternative methods for de-spin or to investigate the Lander "suction", an aerodynamic interaction from the rotor downwash on one side of the Lander body that results in a yaw moment from the body that counters the intended yaw moment from rotor thrust. A sample Q1 rotor sequence versus time is depicted in Figure 12. Adjustments to the stepped RPM magnitudes and dwell times were made during testing to avoid structural dynamics modes and to improve confidence in data quality.

Table 2 Lander rotor sequences

Name	Description	Purpose
Q1	Step and pause rotors 5/7 from 100 to 1100 Titan RPM (~345 to 3800 RPM for test)	Baseline method for positive lander yaw moment
Q2	Dynamically ramp rotors 5/7 from 100 to 1100 Titan RPM (~345 to 3800 RPM for test)	Baseline dynamic method for positive lander yaw moment
Q3	Step and pause rotors 2/4 from 100 to 600 Titan RPM (~345 to ~2100 RPM for test)	Investigate lander body "suction" force that opposes desired lander yaw moment
Q4	Dynamically ramp rotors 2/4 to 600 RPM Titan (~2100 RPM in test)	Investigate lander body "suction" force that opposes desired lander yaw moment
Q5	Step and pause rotors 2/4/5/7 from 100 to 1100 Titan RPM (~345 to 3800 RPM for test)	Alternative method to Q1 for positive lander yaw moment
Q6	Step and pause rotors 1/3/5/7 from 100 to 1100 Titan RPM (~345 to 3800 RPM for test)	Alternative method to Q1 for positive lander yaw moment
Q7	Step and pause rotors 6/8 from 100 to 1100 Titan RPM (~345 to 3800 RPM for test)	Baseline method for negative lander yaw moment (opposite of Q1)
Q8	Dynamically step rotors 6/8 to 1100 Titan RPM (3800 RPM for test)	Baseline dynamic method for negative lander yaw moment (opposite of Q1)
A5	Step and pause all rotors from 100 to 1100 Titan RPM (~345 to 3800 RPM for test)	Also was used in the 2023 14x22 test
Note: Rotors that are not mentioned above are at idle rotational speed (~345 RPM)		

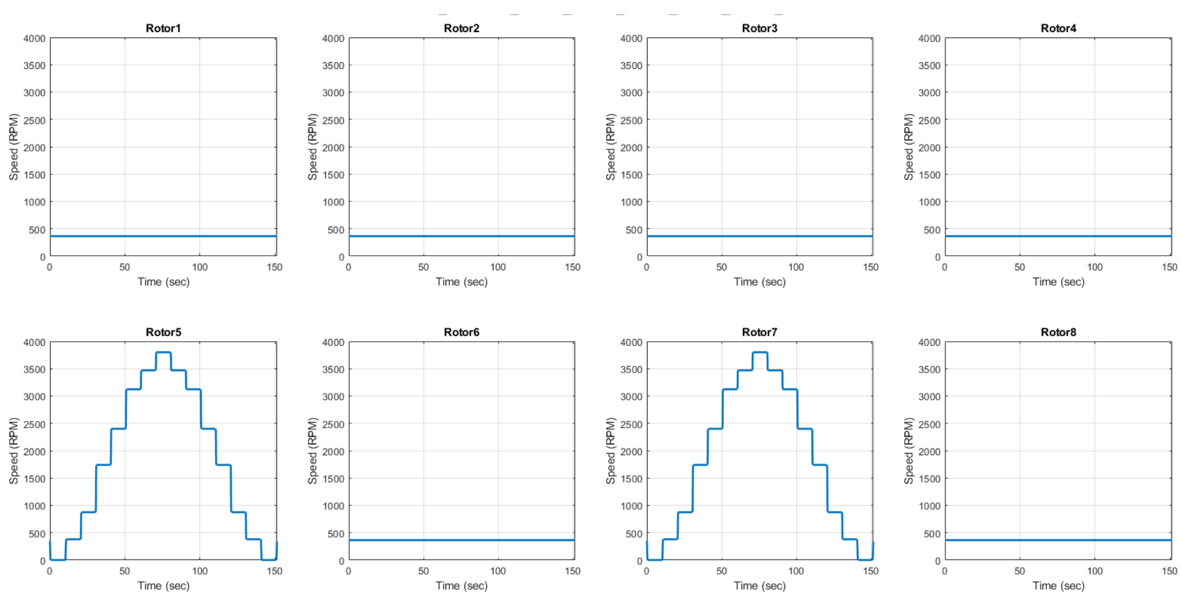


Figure 12 Sample Q1 rotor sequence

Completed Test Runs

A summary of all test runs is shown in Table 3. Each run consisted of a series of test points that involved a combination of tunnel test section speed, Lander pitch angle, Lander roll angle, and Lander rotor sequence. The table includes runs that were scrubbed due to various data system and tunnel operation errors related to power, drive fans, and the turntable. Approximately 13,000 total research test points were completed, which includes the individual stepped rotor RPM levels.

Table 3 Test run summary

Date	Run	Points	Description	Notes	Run Type
1/3/24	1	5	Aero Tares- Lander Only Rotors Off	SDAS ERROR	Scrubbed
1/3/24	2	51	Aero Tares- Lander Only Rotors Off		Research
1/5/24	3	0	Reference Attitude Rotor Sweeps	SOFDAS only	Scrubbed
1/9/24	4	0	Reference Attitude Rotor Sweeps	SOFDAS only	Scrubbed
1/9/24	5	4	Reference Attitude Rotor Sweeps	Tunnel auto stop	Scrubbed
1/9/24	6	4	Reference Attitude Rotor Sweeps	DAS crash	Scrubbed
1/9/24	7	5	Reference Attitude Rotor Sweeps	DAS crash	Scrubbed
1/9/24	8	28	Reference Attitude Rotor Sweeps		Research
1/9/24	9	66	Lander Only 6.9 m/s		Research
1/10/24	10	22	Q Sequence Checkout (wind off)		Research
1/10/24	11	79	Lander Only 5.3 m/s Priority 2	High wind gusts ~20 kts	Research
1/11/24	12	132	Lander Only 5.3 m/s Priority 1		Research
1/11/24	13	121	Lander Only 4 m/s Priority 1	High temp in A1 bearing	Research
1/12/24	14	100	Lander Only 5.3 m/s Priority 1		Research
1/12/24	15	93	Lander Only 4 m/s Priority 2		Research
1/25/24	16	138	Lander+Backshell, repeat of run 12		Research
1/27/24	17	146	Lander+Backshell, V=6.9 m/s		Research
1/29/24	18	62	Lander+Backshell, V=6.9 m/s PT. 2		Research
1/29/24	19	84	Lander+Backshell, V=5.3 m/s		Research
1/30/24	20	9	Continued Lander+Backshell, V=5.3 m/s	DAS initium error	Scrubbed
1/30/24	21	4	Continued Lander+Backshell, V=5.3 m/s	DAS initium error	Scrubbed
1/30/24	22	89	Continued Lander+Backshell, V=5.3 m/s		Research
2/1/24	23	46	Continued Lander+Backshell, V=5.3 m/s	Turntable issue	Research
2/2/24	24	36	Continued Lander+Backshell, V=5.3 m/s		Research
2/2/24	25	119	Lander+Backshell, V=4 m/s		Research
2/5/24	26	91	Lander+Backshell, Mop-Up		Research

Figure 13 through Figure 15 summarize all test points completed for three test section speeds: 4, 5.3, and 6.9 m/s. The tunnel speeds were derived by matching non-dimensional velocity ratio (vertical descent speed divided by rotor-induced velocity at hover) between NFAC and Titan, assuming maximum rotor speeds of 1100 RPM for Titan and 3800 RPM for the test. Repeat test points are indicated by the larger symbol sizes, and were focused on Lander pitch and roll angles of 90 and 0 degrees, respectively. The highest-priority test section speed of 5.3 m/s corresponds to a Titan speed of 2.7 m/s. The Lander pitch angles of 50 to 130 degrees were defined prior to testing to encompass most of the possible angles estimated using POST2 simulations of Titan PPF. The Lander roll angles of -5 to 30 degrees were limited by the capabilities of the NFAC pitch head.

Final data delivery from NFAC was completed in mid-April. Sikorsky re-processed all data, which included merging the NFAC and JHU-APL data system products and separating out the time periods during which rotor RPM was held constant for stepped sequences. A review of the test data and analysis of the data was held on May 2nd. Final delivery of the processed data from Sikorsky to JHU-APL and NASA is scheduled to be completed by the end of May. Test and data analysis documentation from Sikorsky is also planned for the end of May. Further analysis and documentation will continue to support PPF Peer Review #2 and EDL Phase CDR later in 2024.

Figure 16 shows sample data from the Lander and Backshell balances. The plots show the resulting total yaw moment from the Lander (body and rotors) and Backshell for the Q1 rotor sequence, where a positive yaw moment (M_z) is desired. At each tunnel speed, there are areas where the desired yaw moment sign is achieved, but other areas on the perimeters of the Lander pitch and roll envelope show undesired small positive, and even negative, yaw moment. The combinations of Lander pitch and roll where the undesired yaw moment occurs increase in number with increasing tunnel speed, due to the rotors gradually going deeper into vortex ring state (VRS). The reference material listed at the end of this document detail the test readiness reviews, all test data, analysis of the data, and comparisons between CFD and the data to date.

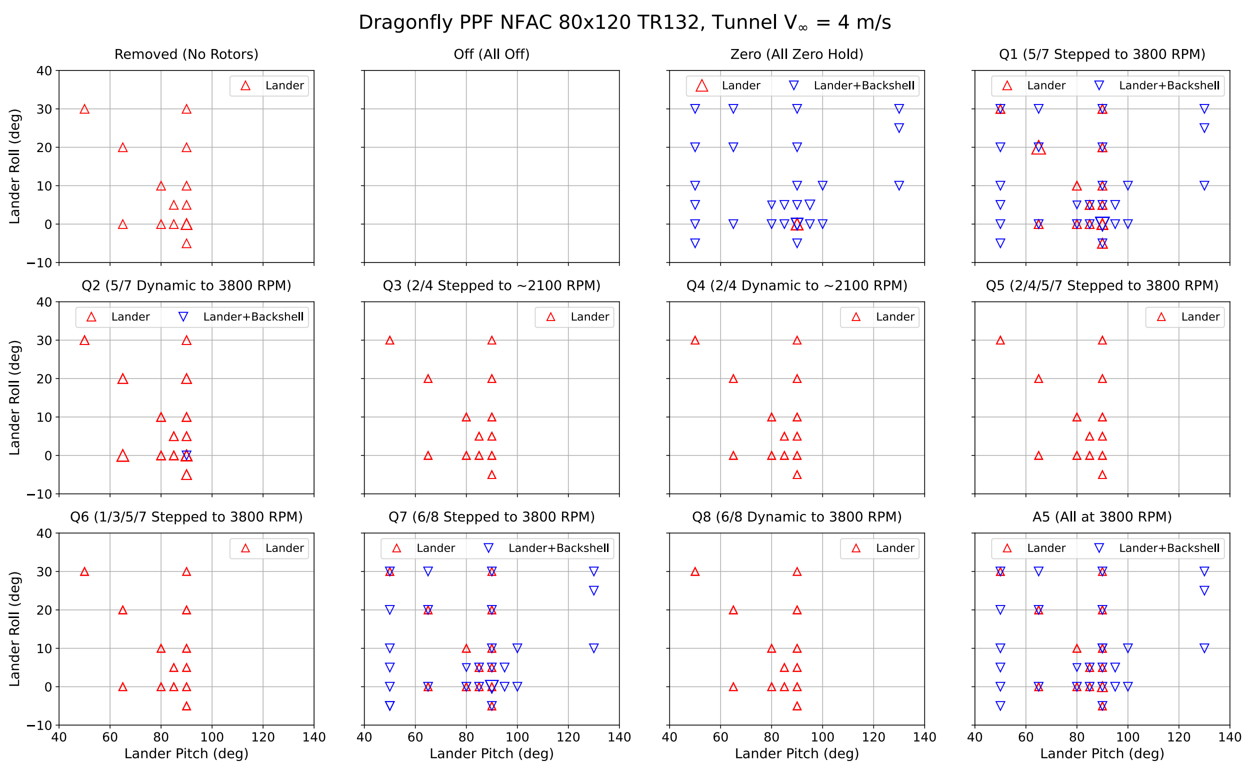


Figure 13 Lander and Lander + Backshell test points at 4 m/s test section speed. Sub-plots are shown for each rotor sequence. Symbol size indicates total count including repeat test points.

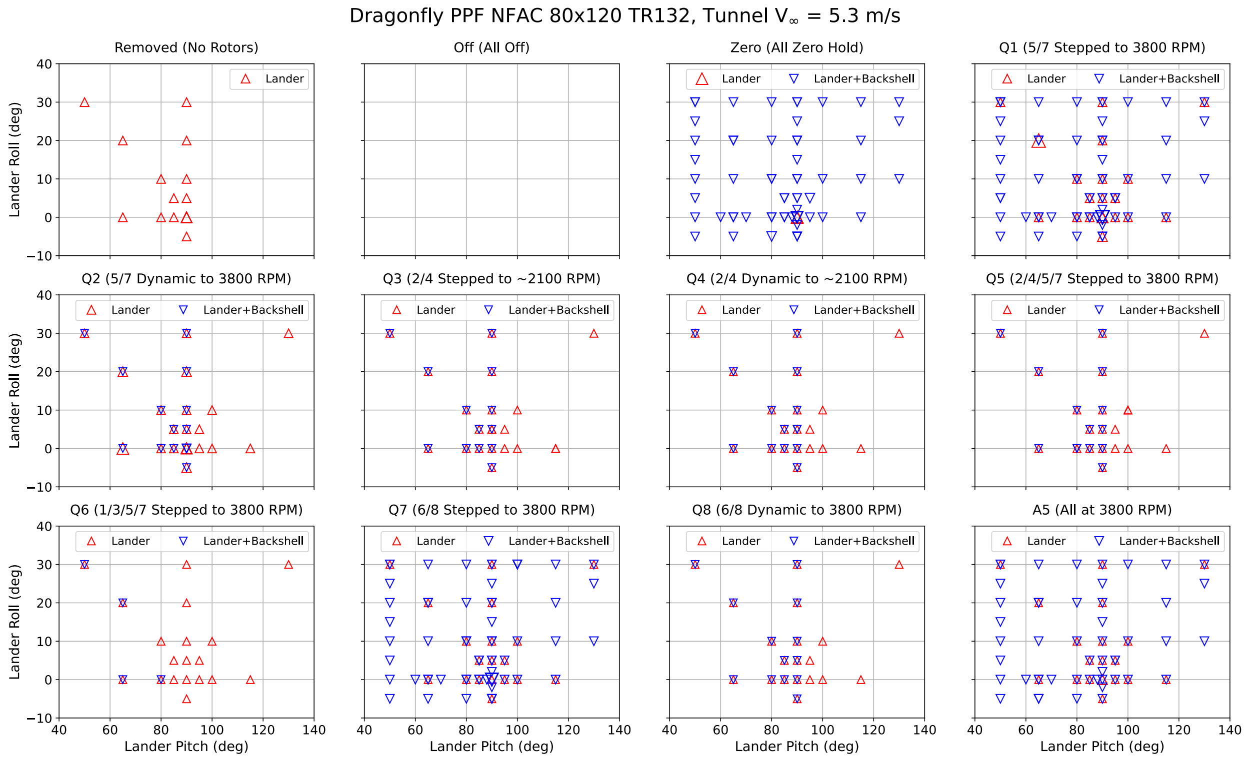


Figure 14 Lander and Lander + Backshell test points at 5.3 m/s test section speed. Sub-plots are shown for each rotor sequence. Symbol size indicates total count including repeat test points.

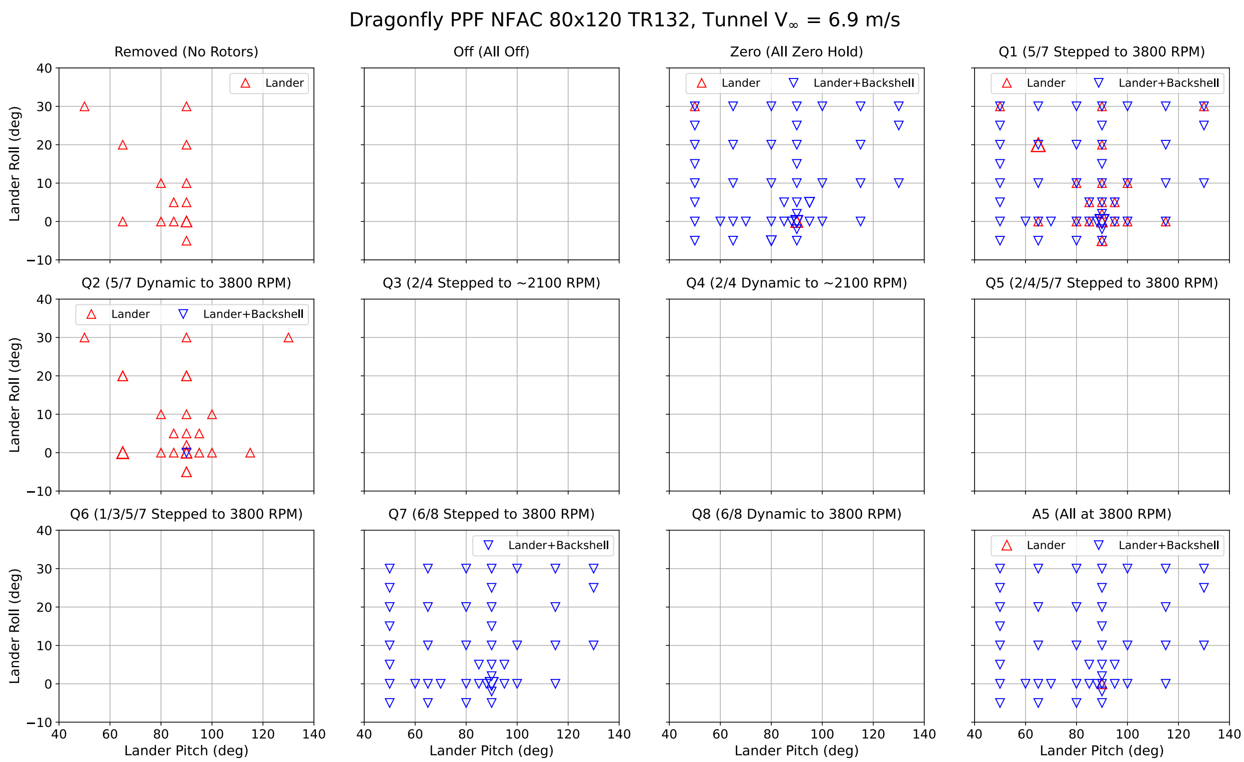


Figure 15 Lander and Lander + Backshell test points at 6.9 m/s test section speed. Sub-plots are shown for each rotor sequence. Symbol size indicates total count including repeat test points.

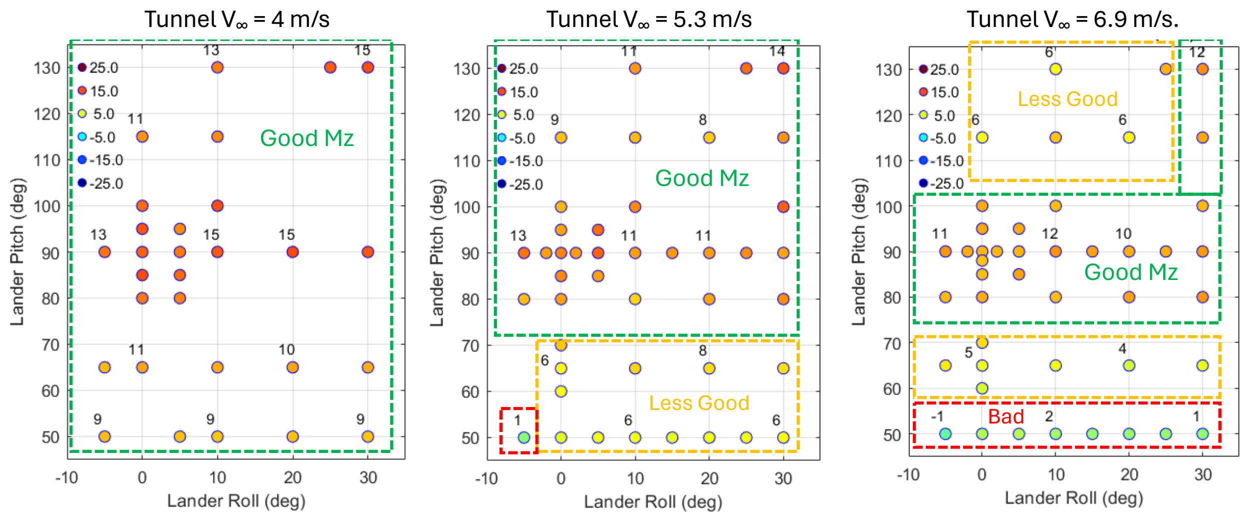
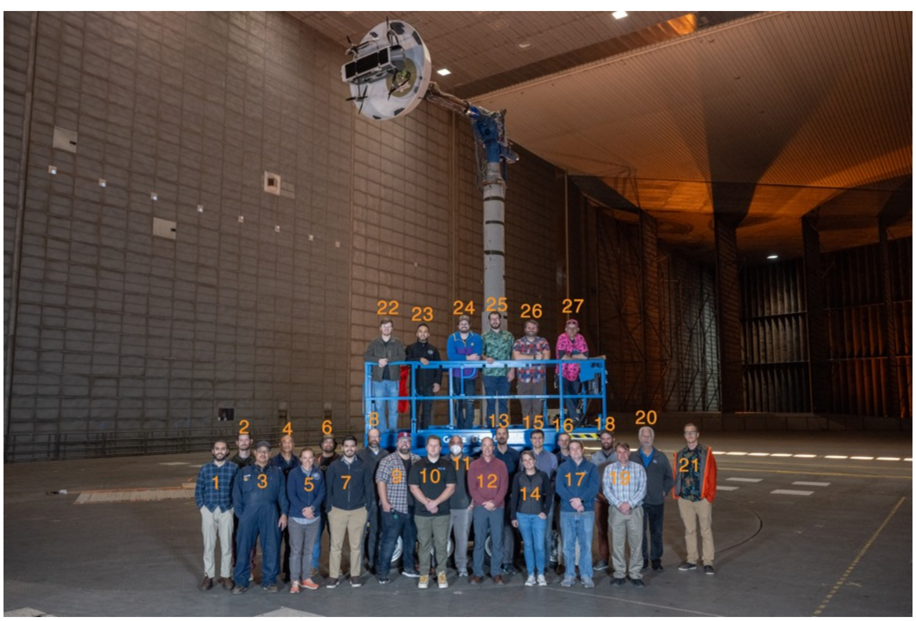


Figure 16 Sample processed test data showing Lander + Backshell total yaw moment (M_z in N-m) at tunnel speeds of 4 m/s (left), 5.3 m/s (middle), and 6.9 m/s (right) for rotor sequence Q1 with rotors 5 and 7 at 3484 RPM (positive M_z is desired). Areas are identified where "good" yaw moment (positive), "less good" moment (positive, but small), and "bad" moment (negative) were measured. Image Credit: Peter Lorber, Sikorsky.

Test Team

The test team is shown in the 80x120 test section in Figure 17. The list below the figure includes personnel and contractors from the Dragonfly project who contributed to the design and fabrication of the new test hardware (Backshell, stings, etc.) and to the planning and execution of the test.



1. Antonio Rivera, Sikorsky
2. Jon Winegar, NFAC
3. Meliton Abenojar, NFAC
4. Bartolome Agenon, NFAC
5. Emily Sayles, NFAC
6. Shawn Abadejos, NFAC
7. Nathan Noma, NFAC
8. Daniel Grieb, NFAC
9. Tyler Pearsall, NFAC
10. Daniel Brookbank, NFAC
11. Joseph Candaso, NFAC
12. Karl Edquist, NASA
13. Matt Misiorowski, APL
14. Stephanie Lepchenske, APL
15. Arturo Zamora, NFAC
16. Jason Cornelius, NASA
17. John Samsock, APL
18. Chris Ward, APL
19. Bill Kellermeyer, APL
20. Johannes M. van Aken, NFAC
21. Chris Nykamp, NFAC
22. James Bailey, NFAC
23. Jose Cabrales, NFAC
24. Ryan Edwards, NFAC
25. Paul Gilles, NFAC
26. Kyle Lukacovic, NFAC
27. Pat Goulding II, NFAC

Figure 17 Test team members (partial) from NFAC, JHU-APL, NASA, and Sikorsky

Table 4 Dragonfly test team

NASA Langley	**JHU-APL**	**NASA Ames**
Edquist, Karl T.	Adams, Dewey	Young, Larry A.
Shellabarger, Eli R.	Burton, Donald E.	Cornelius, Jason K
Fell, Jared	Drewicz, Anthony W.	Wagner, Lauren N.
Geissinger, Stephen K.	Forina-Morales, Francesco G.	
Tomek, William G.	Hauffe, Richard N.	**Sikorsky Aircraft**
Commo, Sean A.	Hebert, Chuck	Lorber, Peter
Pillari, Adam R.	Heisler, Richard R.	Wallace, Brian
McLain, Christopher K.	Kellermeyer, Bill	Sharma, Kalki
Girard, William	Lepchenske, Stephanie D.	Gruber, Kate
Lovaglio, Danny J.	McGrath, Brian E.	Vermillion, Therese-Ann
Tofts, Philip J.	Misiorowski, Matt	Rivera, Antonio
Tilley, David E.	Miura, Kentaro	Bowles, Patrick
Whaley, Chase D.	Samsock, John J.	
Johnson, Timothy J.	Savery, Thaddeus J.	
Ahmic Aerospace LLC	Ward, Christopher A.	
Modern Machine & Tool Co. Inc		

Reference Material

- Charts from Lander (16 October 2023) and Test Readiness Reviews (18 October 2023):
  - NASA Box
  - JHU-APL Sharepoint
- Charts from Dragonfly NFAC 80x120 PPF Test Data and Analysis Review, held on 2 May 2024:
  - NASA Box
  - JHU-APL Sharepoint

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