Wind Tunnel Testing Techniques for a Tandem Tilt-Wing, Distributed Electric Propulsion VTOL Aircraft

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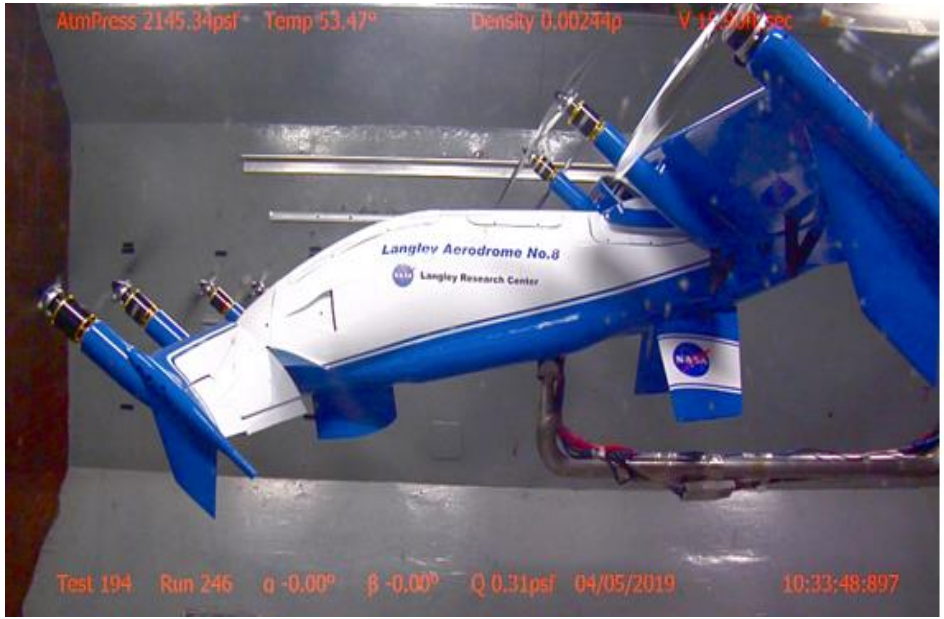
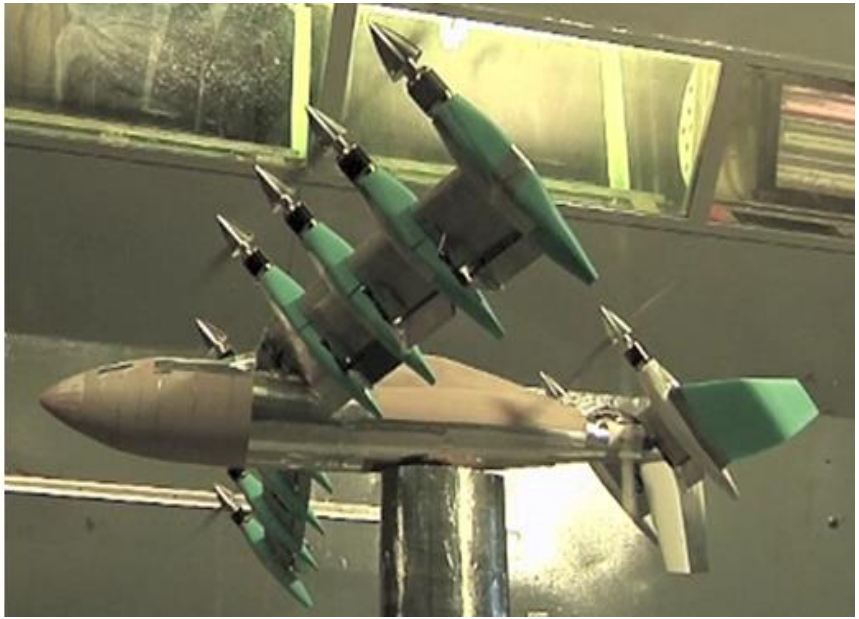
LA-8 and GL-10 Being Tested in the 12-Foot Tunnel

LA-8



GL-10



LA-8 testing techniques built upon prior experience testing the GL-10.

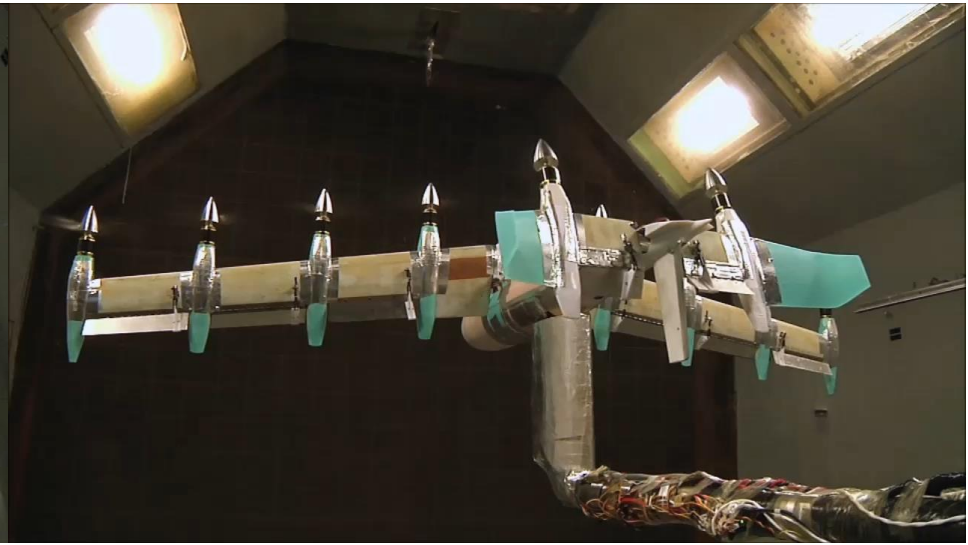
One factor at a time (OFAT) testing

Design of experiment (DOE) testing

LA-8 and GL-10 DOE Testing Sample Videos

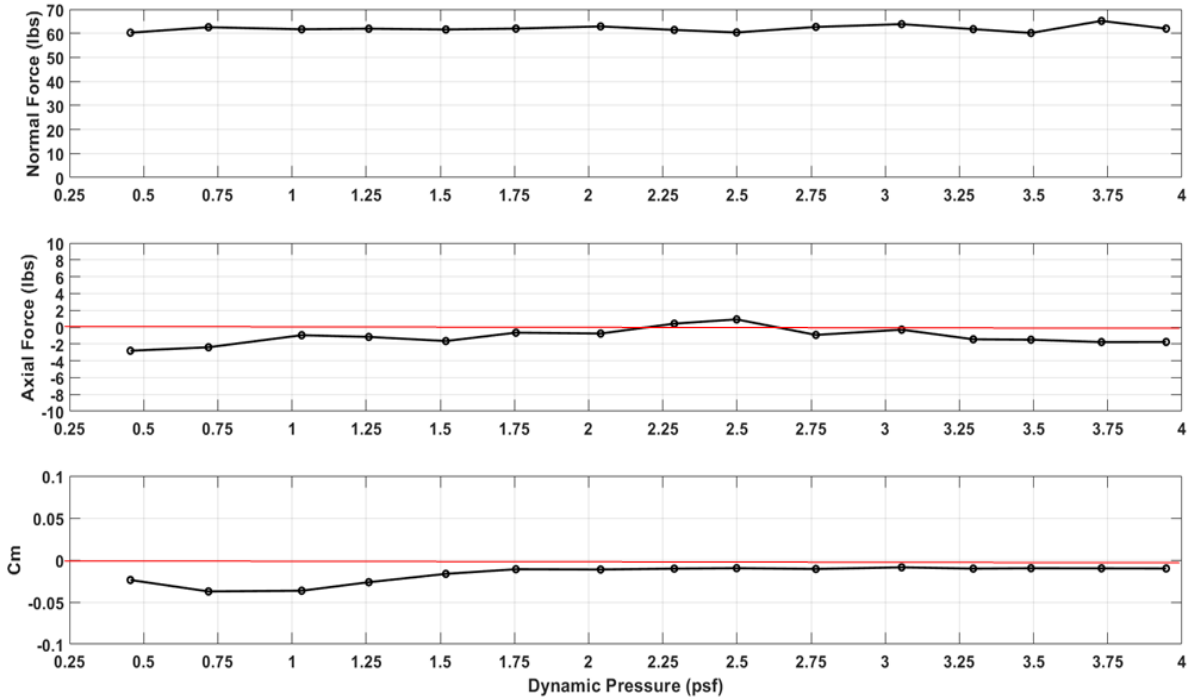
LA-8

GL-10



GL-10 wind tunnel testing was almost exclusively DOE.
LA-8 wind tunnel testing combined OFAT and DOE methods.

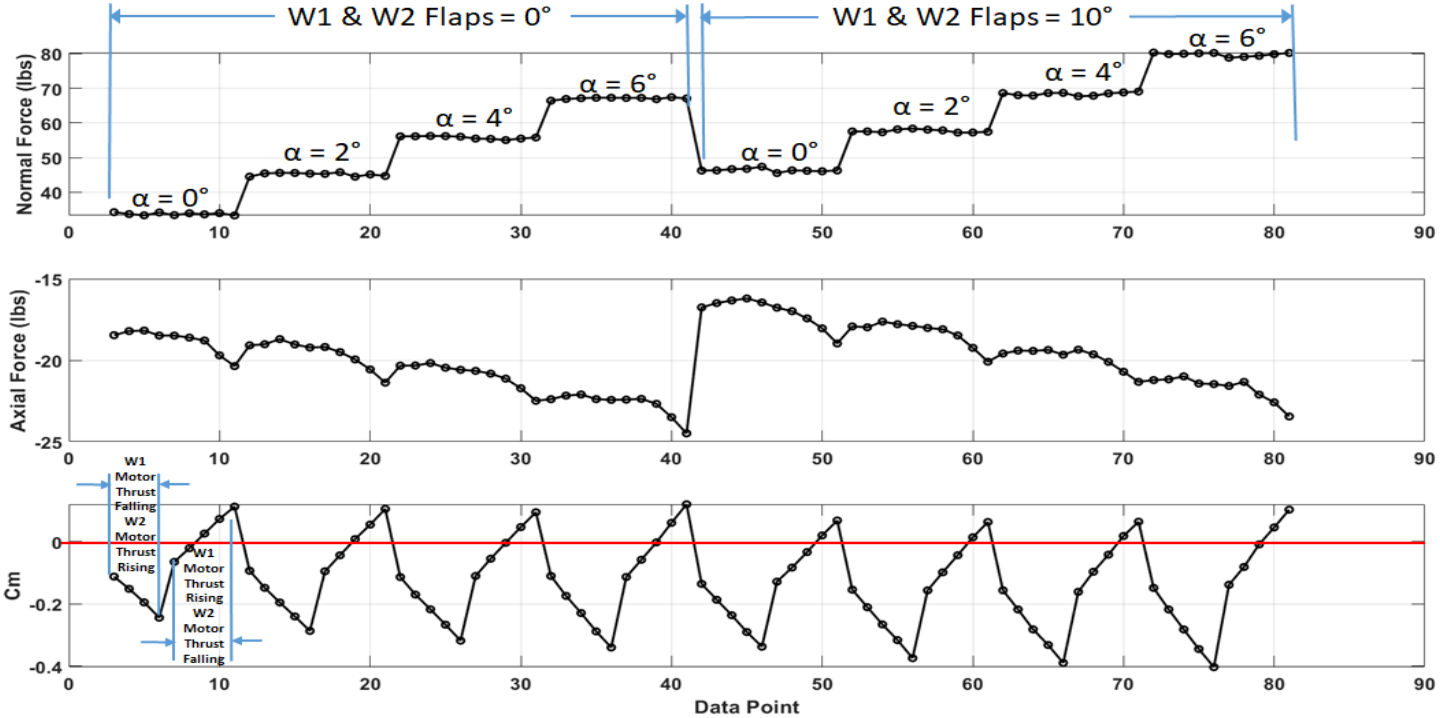
LA-8 Normal Force, Axial Force, & C_m for "Trim" Points



Q (psf)	Alpha (Deg)	Wing 1 Angle (Deg)	Wing 2 Angle (Deg)	All Four Flaps (Deg)	All Four Elevons (Deg)	Both Ruddervators (Deg)
0	0	82	82	0	0	0
0.5	0	56	56	0	0	0
0.75	0	51	51	0	0	0
1	0	47	47	0	0	0
1.25	0	43.5	43.5	0	0	0
1.5	0	38	38	0	0	0
1.75	0	35	35	0	0	0
2	0	32	32	0	0	0
2.25	0	30	30	0	0	0
2.5	0	27	27	0	0	0
2.75	0	23	23	0	0	0
3	0	21	21	0	0	0
3.25	0	18.5	18.5	0	0	0
3.5	0	16	16	0	0	0
3.75	0	16*	16*	0	0	0
4	0	14	14	0	0	0

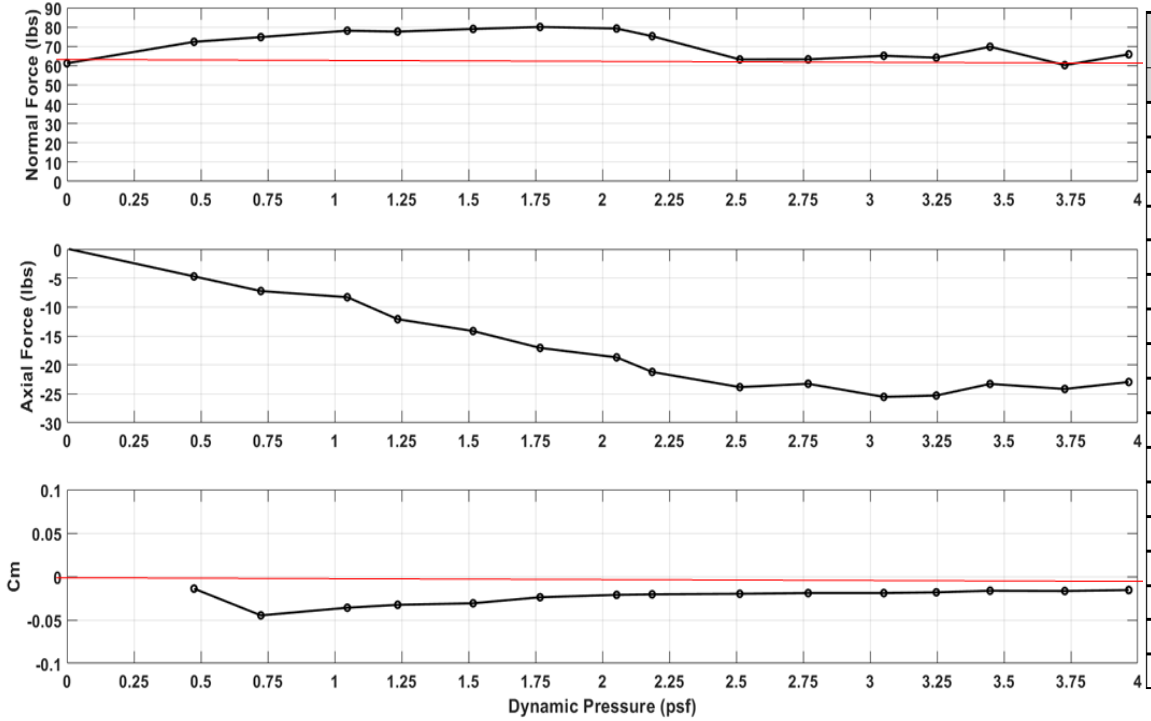
OFAT testing was used to determine critical vehicle parameter settings for steady-state longitudinally trimmed points for LA-8 transitioning from hover to slow forward flight.

Wing1/Wing2 Differential Thrust for Pitch Control



OFAT sweeps of control effector settings about previously determined longitudinal trim points provided initial assessments of control authority in pitch, roll, & yaw.

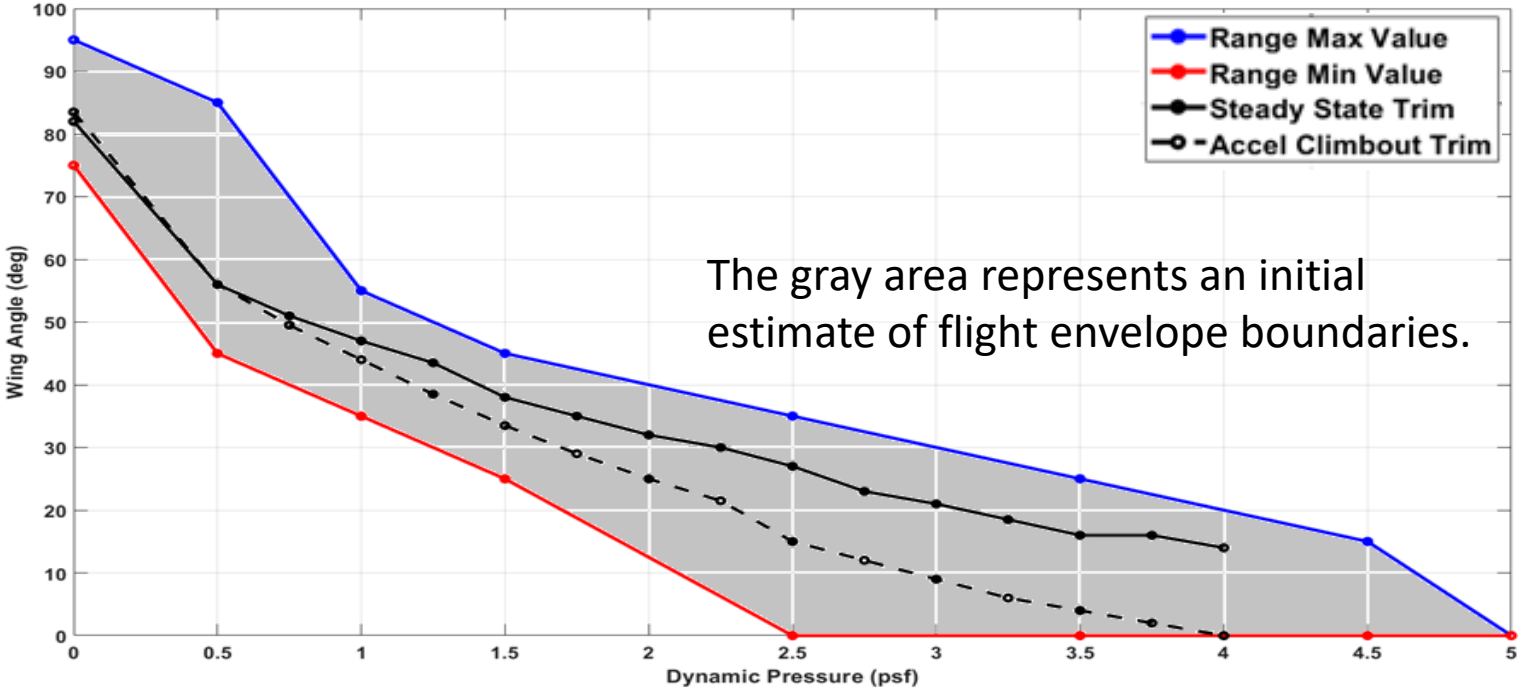
Normal force, Axial Force, and C_m for LA-8 Run Simulating Accelerating Climbout



Q (psf)	Alpha (Deg)	Wing 1 Angle (Deg)	Wing 2 Angle (Deg)	Flap 1 (Deg)	Flap 2 (Deg)	Flap 3 (Deg)	Flap 4 (Deg)	All Four Elevons (Deg)	Both Ruddervators (Deg)
0	0	84.5	84.5	0	0	0	0	0	0
0	0	83.5	83.5	0	0	0	0	0	0
0.5	0	56	56	0	0	0	0	0	0
0.75	0	49.5	49.5	0	0	0	0	0	0
1	0	44	44	0	0	0	0	0	0
1.25	0	38.5	38.5	0	0	0	0	0	0
1.5	0	33.5	33.5	0	0	0	0	0	0
1.75	0	29	29	0	0	0	0	0	0
2	0	25	25	0	0	0	0	0	0
2.25	0	21.5	21.5	0	0	0	0	0	0
2.5	0	15	15	0	0	5	5	0	0
2.75	1	12	12	5	5	10	10	0	0
3	2	9	9	10	10	15	15	0	0
3.25	3	6	6	15	15	20	20	0	0
3.5	4	4	4	20	20	25	25	0	0
3.75	5	2	2	15	15	20	20	0	0
4	6	0	0	20	20	25	25	0	0

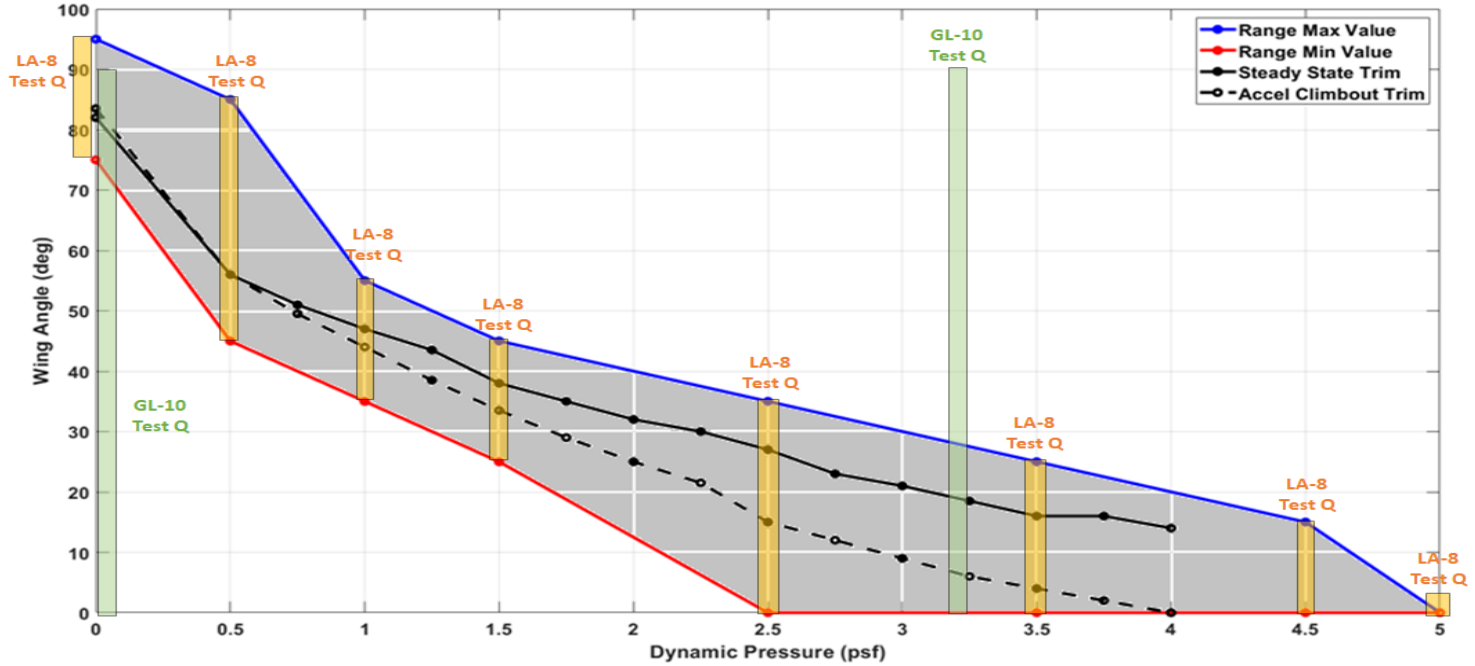
OFAT testing was used to determine critical vehicle parameter settings for a simulated accelerating LA-8 climbout from hover to slow forward flight.

LA-8 OFAT Trim Point Wing Angles and DOE Wing Angle Range Limits



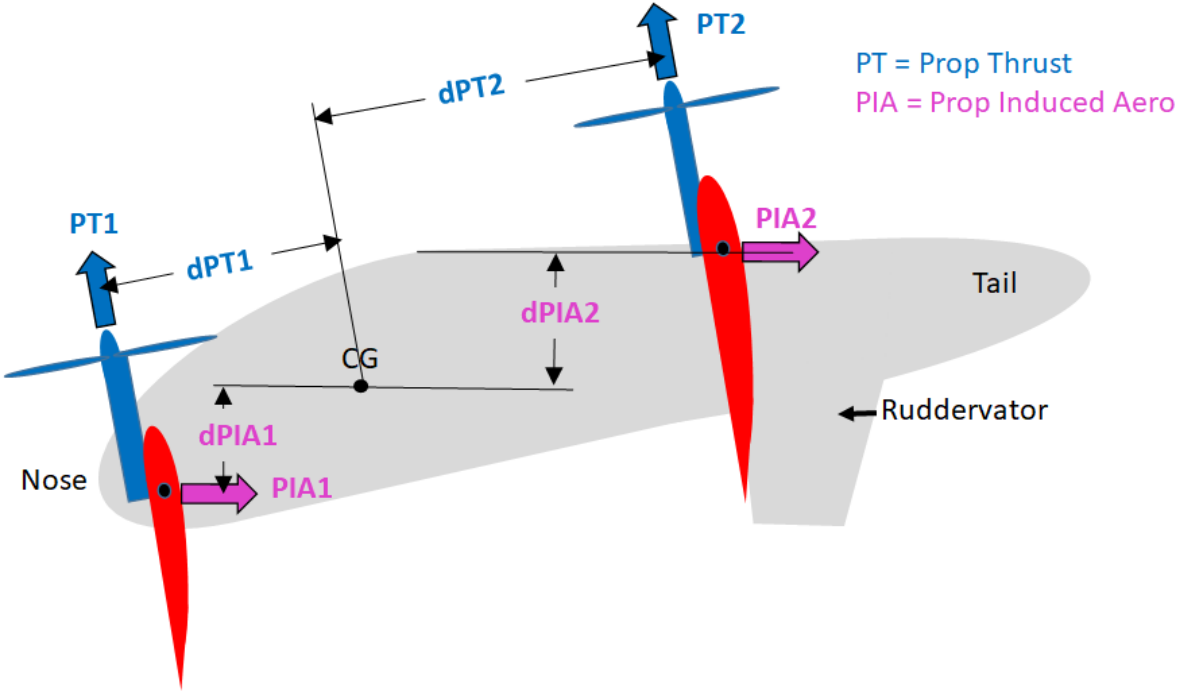
OFAT assessments of control authority and transitioning from hover to forward flight were used to set critical independent variable ranges for subsequent LA-8 DOE testing.

LA-8 and GL-10 DOE Test Dynamic Pressures and Wing Angles



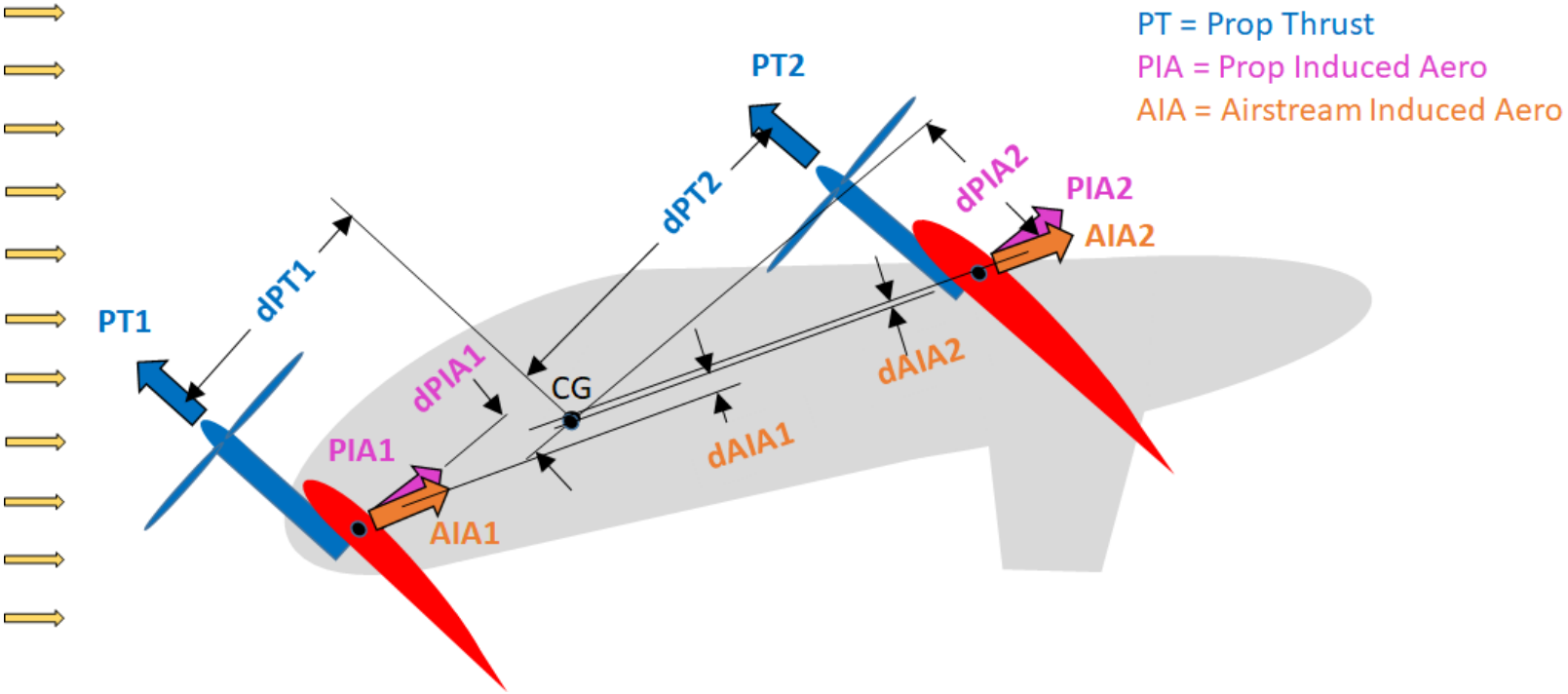
LA-8 DOE data covered the transition flight envelope better than GL-10 data.
Significant portions of the GL-10 data collected was outside the likely flight envelope.

LA-8 Forces in a No-Wind Stationary Hover
(Contributions to Pitching Moment)



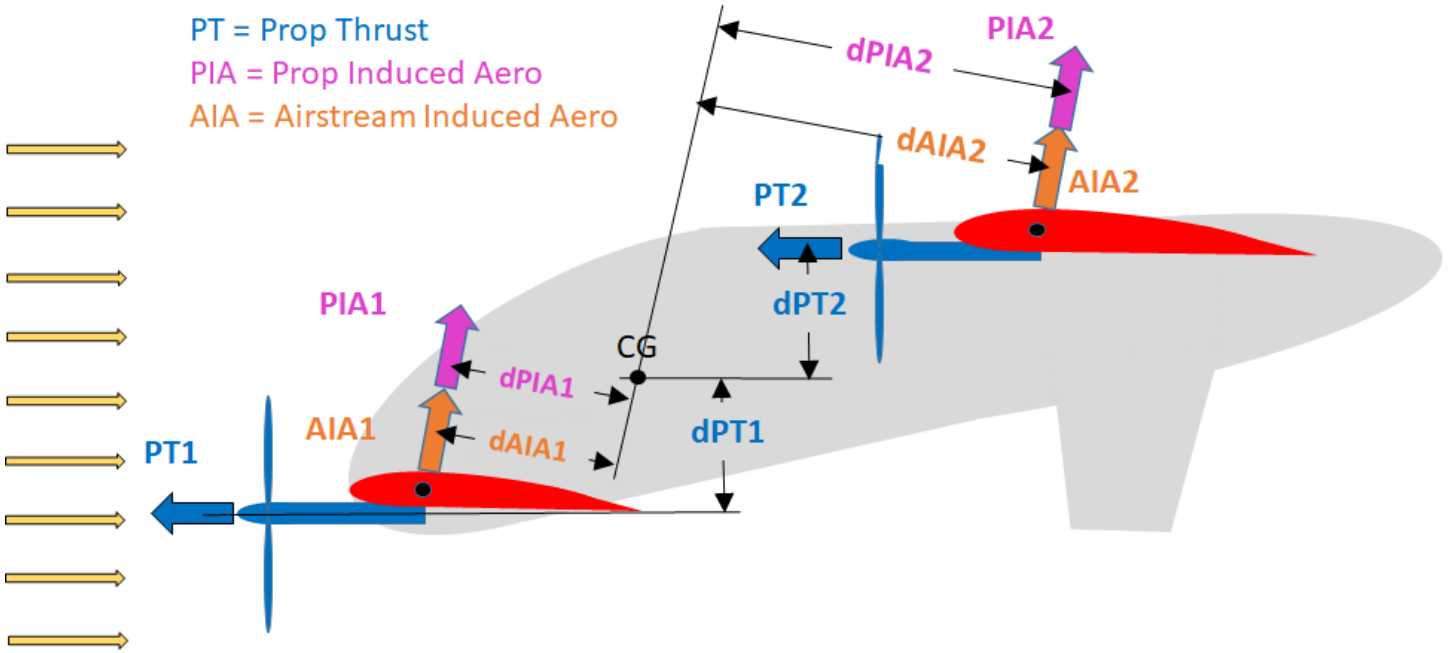
In hover the blown wing aero forces produce vehicle pitching moment increments in the opposite direction from those produced by propeller thrust.

LA-8 Forces in Mid-Transition Between Hover and Forward Flight (Contributions to Pitching Moment)



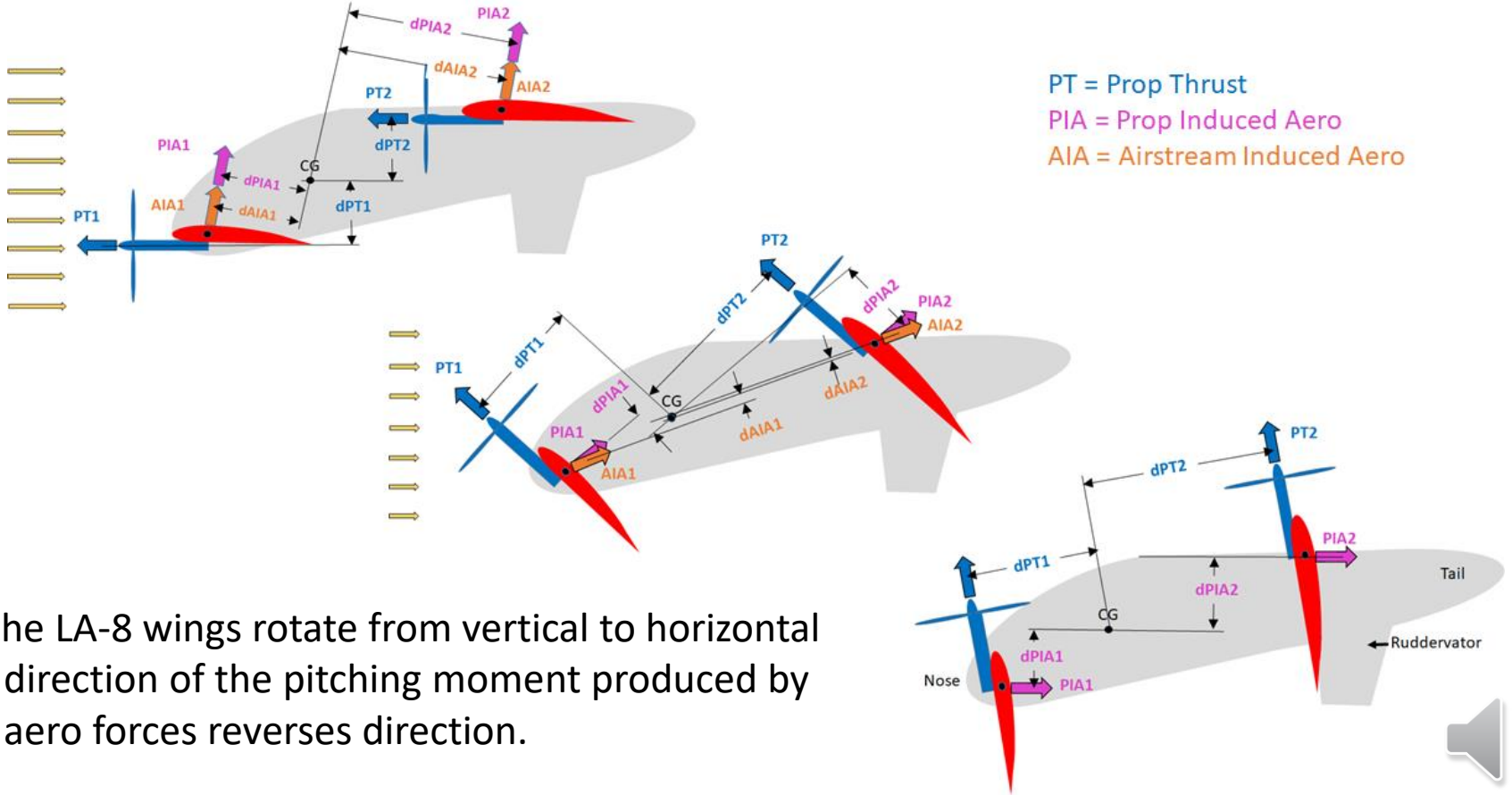
Effective moment arms for wing aero forces get smaller as the wings rotate away from hover positions.

LA-8 Forces in Cruising Forward Flight
(Contributions to Pitching Moment)



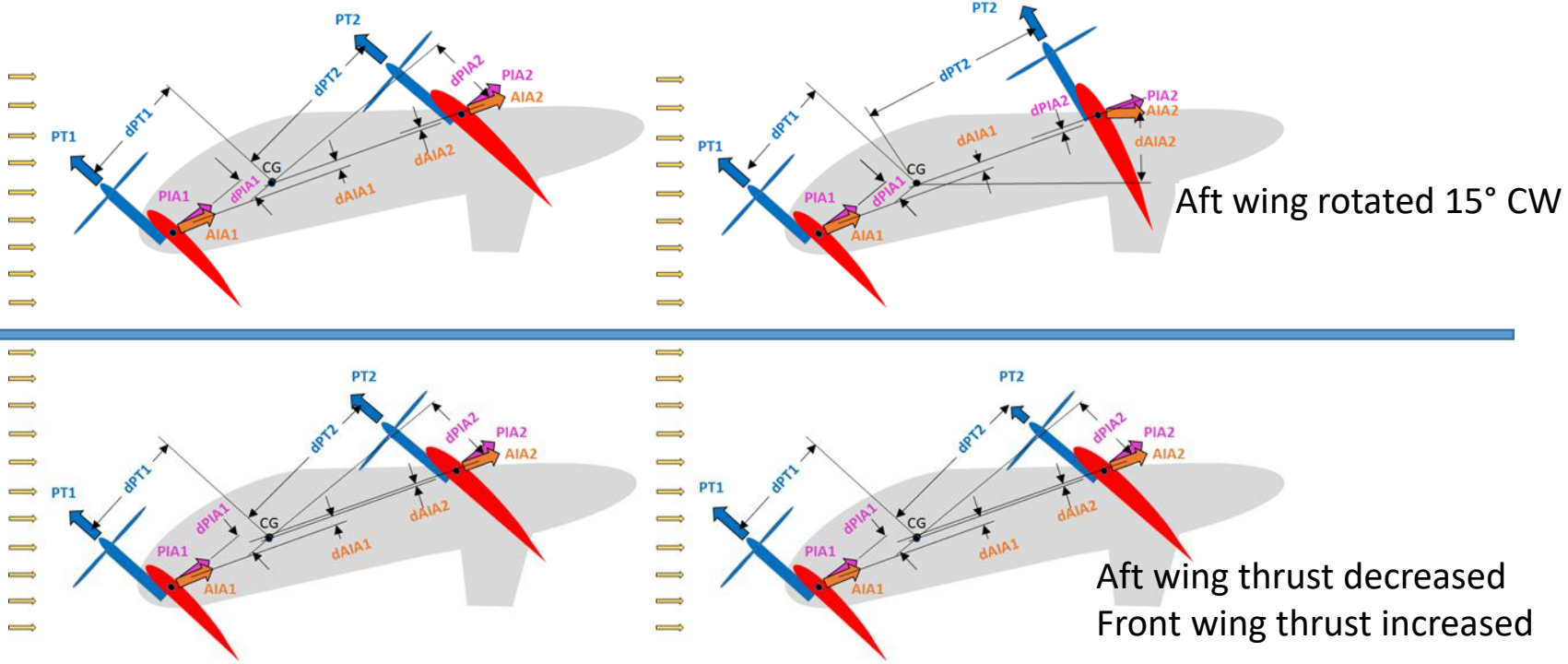
In the forward flight configuration the propeller and all aero forces for a wing produce pitching moment increments in the same direction.

Changing Pitching Moment Contributions as the LA-8 Wings Rotate



As the LA-8 wings rotate from vertical to horizontal the direction of the pitching moment produced by the aero forces reverses direction.

Differential Wing Tilt vs Differential Front-Aft Wing Propeller Thrust for Pitch Control

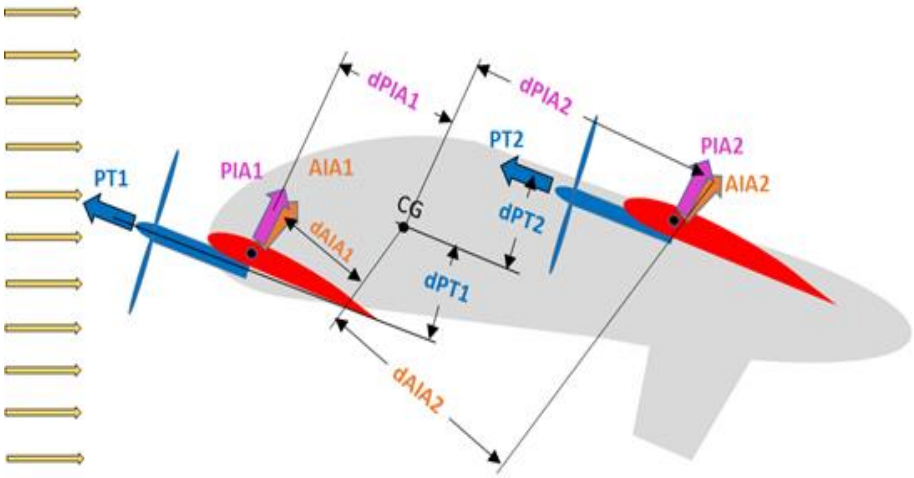


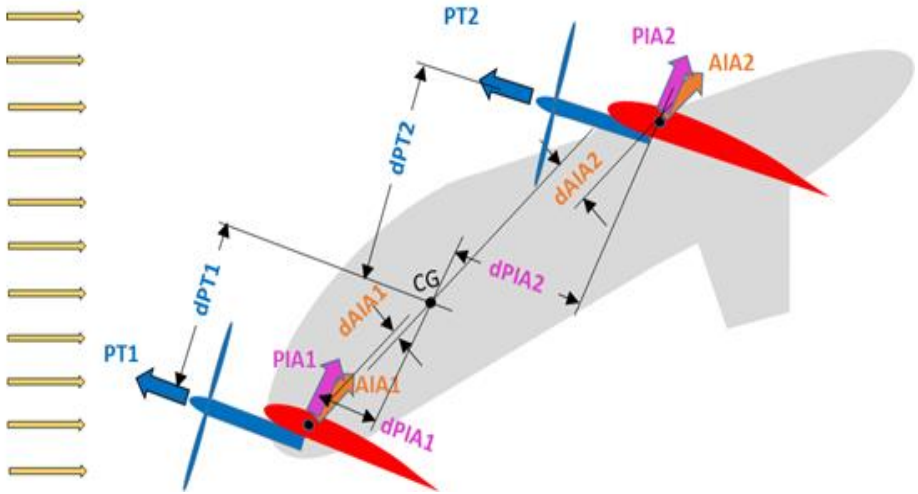
Aft wing rotated 15° CW

Aft wing thrust decreased
Front wing thrust increased

Differential thrust between the front and aft wing propellers was found to be much more effective for pitch control than differential wing tilt.

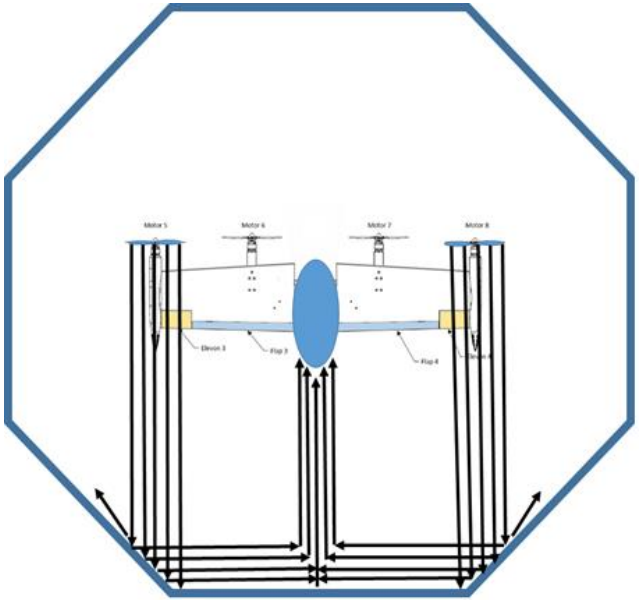
LA-8 Attitude Options for Slow Forward Flight

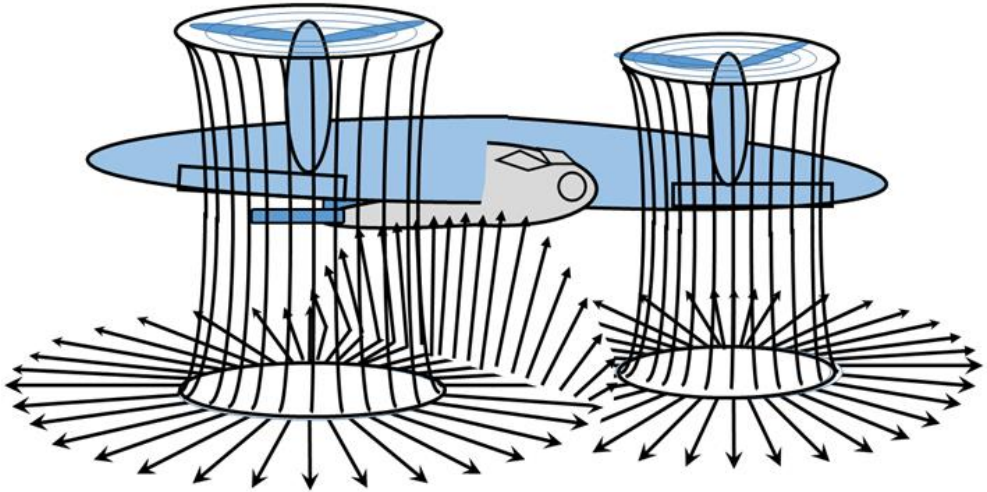




Tandem tilt-wing VTOL configurations like LA-8 have multiple vehicle orientation options for some parts of the flight envelope, with potentially very different performance characteristics.

Tunnel Wall/Ceiling/Floor Effects & Ground Effect





Significance of tunnel wall, ceiling, and floor effects on initial LA-8 hover testing results TBD.

Future LA-8 hover testing to include mounting the airframe vertically so propeller flow is aligned with the normal flow through the test section.

Conclusions

- DOE is currently the only practical alternative for obtaining all the aerodynamic interaction data for complex VTOL vehicles like LA-8.
- An initial OFAT test can be very useful for:
  - Assessing whether there is sufficient thrust and control authority to execute a longitudinally trimmed transition between hover and forward flight.
  - Evaluating control authority in pitch, roll, and yaw through the transition between hover and forward flight.
  - Determining the independent variable ranges to keep the subsequent DOE testing points within the likely flight envelope for the vehicle.
  - Gaining insight into the vehicle's performance characteristics
- The LA-8's tilt wings make the pitching moment characteristics of the vehicle very complex, with some contributions changing direction somewhere between hover and forward flight.
- Differential front-aft wing propeller thrust is far more effective than differential wing tilt for controlling the LA-8's pitch attitude.
- Initial LA-8 hover testing results need to be further assessed to determine the character and significance of the 12-Foot Tunnel wall, floor, and ceiling effects on performance.

Questions?

Design, Testing, and Modeling for the LA-8 Tilt-Wing VTOL Aircraft I & II References

1. North, D. D., Howland, G., and Busan, R. C., “Design and Fabrication of the LA-8 Distributed Electric Propulsion VTOL Testbed”
2. **Busan, R. C., Murphy, P. C., Hatke, D. B., and Simmons, B. M., “Wind Tunnel Testing Techniques for a Tandem Tilt-Wing, Distributed Electric Propulsion VTOL Aircraft”**
3. Simmons, B. M., “System Identification for Propellers at High Incidence Angles”
4. Geuther, S. C., and Fei, X., “LA-8 Computational Analysis and Validation Studies Using FlightStream”
5. Simmons, B. M., and Murphy, P. C., “Wind Tunnel-Based Aerodynamic Model Identification for a Tilt-Wing, Distributed Electric Propulsion Aircraft”
6. North, D. D., “Flight Testing of a Scale Urban Air Mobility Technology Testbed” (Presentation Only)