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

Ronald C. Busan,[1] Patrick C. Murphy,[2] David B. Hatke,[3] and Benjamin M. Simmons[4]

NASA Langley Research Center, Hampton, VA, 23681

Urban Air Mobility (UAM) vertical takeoff and landing (VTOL) aircraft designs frequently include multiple distributed propulsors, complex wing-propulsor aerodynamics, significant airframe configuration changes during normal flight operations, and no historical database regarding the best ways to transition between vertical and horizontal flight. This paper describes the methodology used for wind tunnel testing of the Langley Aerodrome No. 8 (LA-8) in the NASA Langley 12-Foot Low-Speed Tunnel during multiple test entries in 2019 and 2020. The LA-8 is a tandem tilt-wing aircraft with 4 motor-propeller units and 4 control surfaces distributed across each wing, plus an inverted V-tail with 2 ruddervators on the fuselage. An initial tunnel entry used one-factor-at-a-time (OFAT) testing to (1) define candidate trimmed transition corridors between vertical and horizontal flight, (2) assess whether there was adequate control authority, and (3) define appropriate test factor ranges for subsequent design of experiment (DOE) wind tunnel testing. The total number of independent variables for these wind tunnel tests (23) made DOE testing an efficient option for assessing the large number of potential interactions associated with the LA-8. The general advantages and disadvantages of OFAT and DOE wind tunnel testing techniques are also discussed – along with the benefits of a combined approach.

I. Nomenclature

C_L	=	lift coefficient
C_D	=	drag coefficient
C_m	=	pitching moment coefficient
α	=	angle of attack, deg
β	=	sideslip angle, deg
PT1	=	wing 1 propeller thrust
PT2	=	wing 2 propeller thrust
dPT1	=	distance from wing 1 propeller thrust to CG
dPT2	=	distance from wing 2 propeller thrust to CG
PIA1	=	wing 1 propeller induced aerodynamic force
PIA2	=	wing 2 propeller induced aerodynamic force
dPIA1	=	distance from wing 1 propeller induced aero to CG
dPIA2	=	distance from wing 2 propeller induced aero to CG
AIA1	=	wing 1 airstream induced aerodynamic force
AIA2	=	wing 2 airstream induced aerodynamic force
dAIA1	=	distance from wing 1 airstream induced aero to CG
dAIA2	=	distance from wing 2 airstream induced aero to CG

II. Introduction

Technology developments in distributed electric propulsion, higher capacity lightweight batteries, and improved stability and control augmentation has spawned development of a wide range of new vertical takeoff and landing (VTOL) configurations. Wind tunnel testing has historically played an important role in any aircraft development program, and the variety and complexity of many of the new VTOL configurations pose new challenges for how wind

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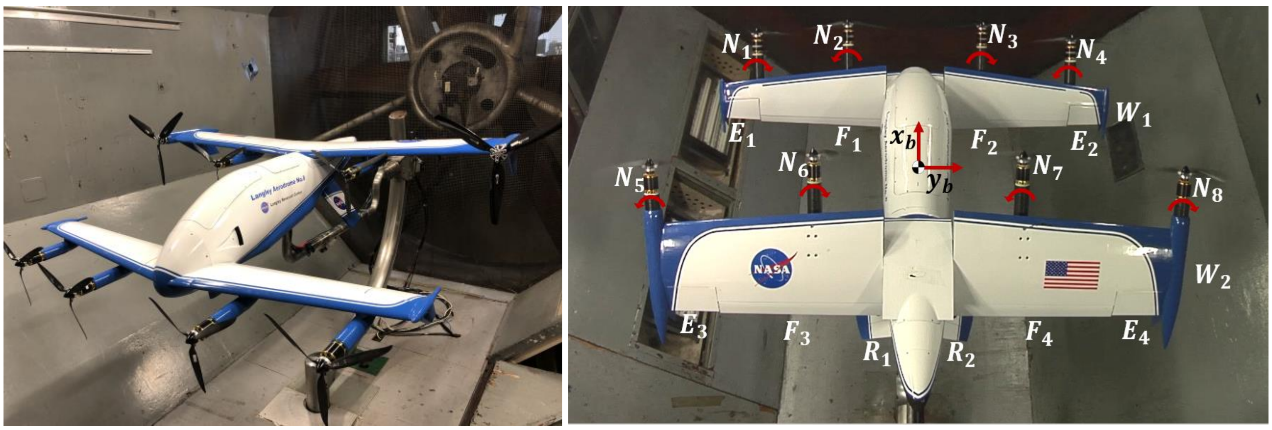
[1] Senior Research Engineer, Flight Dynamics Branch, MS 308, AIAA Member.
[2] Senior Research Engineer, Dynamic Systems and Control Branch, MS 308, AIAA Associate Fellow.
[3] Research Engineer, Flight Dynamics Branch, MS 308, AIAA Member.
[4] Research Engineer, Flight Dynamics Branch, MS 308, AIAA Member.

tunnel testing should be conducted. In 2013, testing of the GL-10 tilt-wing tilt-tail 10-motor airframe with 29 independent variables in the Langley 12-Foot Low-Speed Wind Tunnel highlighted the need to incorporate design of experiment (DOE) and response surface methods (RSM) into the testing process. In this paper references to DOE are intended in the general sense to include both DOE and RSM. Lessons learned from the GL-10 wind tunnel tests were incorporated into the 2019 and 2020 testing of the LA-8 airframe shown in Fig. 1. Figure 2 shows a side-by-side comparison of the LA-8 and GL-10 airframes as tested in the 12-Foot Tunnel. Reference [1] documents the 2013 GL-10 wind tunnel test, describes the test faculty capabilities, gives a history of the DOE testing conducted in the 12-Foot Tunnel since 2002, provides examples of the GL-10 data obtained, and discusses model requirements and the facility hardware/software modifications needed to implement the DOE testing approach. In many ways the current paper can be considered a direct follow-on to that prior document. References [2] and [3] provide additional details about the GL-10 2013 DOE data collection and subsequent modeling and simulation work done with that data.



(a) View from front left **(b) View from top aft, showing all control effectors**

Fig. 1 LA-8 mounted in the NASA Langley 12-Foot Low-Speed Tunnel.

A number of conference papers and NASA technical memorandums provide extensive documentation about the LA-8 research testbed and the recent testing and modeling work associated with the aircraft. Design, fabrication, load testing, and mass property assessments of the LA-8 airframe are described in Refs. [4] and [5]. The full one-factor-at-a-time (OFAT) test results are presented in Ref. [6] and isolated propeller testing is described in Ref. [7]. Use of the LA-8 powered airframe DOE test data and development of the LA-8 aerodynamic models are described in Refs. [8], [9], and [10].

The primary focus of the current paper is to provide a better understanding of how the LA-8 was tested, how the testing built upon the lessons learned from the GL-10 tests, and describe the practical benefits and potential issues. A secondary goal is to provide some physics-based insight into LA-8's unusual pitching moment characteristics.

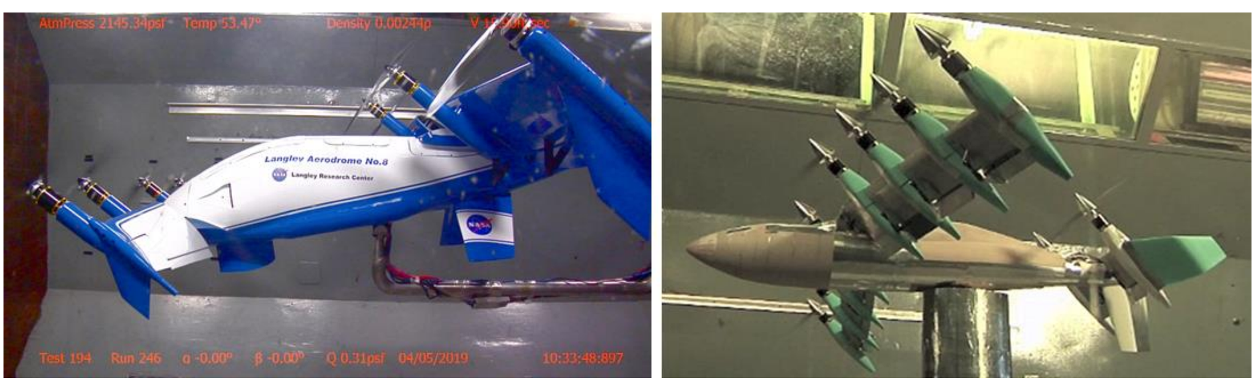


Fig. 2 Side-by-side comparison of the LA-8 and GL-10 airframes in the 12-Foot Tunnel.

This paper is organized as follows: Section III looks at the advantages and disadvantages of several wind tunnel testing techniques. Section IV lists the major lessons learned from wind tunnel testing of GL-10 in 2013. Section V describes the initial OFAT testing of LA-8 done in the spring of 2019. Section VI includes discussion of LA-8's pitching moment characteristics and control options, with an emphasis on establishing a better understanding of the physics involved. Section VII describes the LA-8 configuration changes made immediately after the spring of 2019 OFAT testing. Section VIII includes some clarifying comments about the DOE testing done in the summer of 2019. Section IX briefly discusses component testing and the buildup approach as it applies to LA-8 and other VTOL configurations. Section X describes potential issues with the LA-8 initial hover testing results. Section XI includes an initial comparison of LA-8 OFAT and DOE test results plus a description of planned additional wind tunnel testing, and Sec. XII has concluding summary remarks.

III. Wind Tunnel Testing Approach Tradeoffs

OFAT and DOE wind tunnel testing approaches each have their own advantages (pros) and disadvantages (cons). The following sections highlight some of the most important pros and cons for each method to consider when developing a wind tunnel test plan, with the best option often being a combination of both approaches.

A. OFAT Testing Pros:

OFAT testing is a traditional experiment design approach where all known factors, except the one currently under test, are held constant. OFAT wind tunnel testing has the following advantages:

1. ***OFAT testing is typically easy to set up and implement for systems with limited complexity.*** Sweeping through the range of a single factor while holding all other factors constant is a simple process to implement at most wind tunnel facilities. Exploratory work to capture a broad understanding of the test article response features, and detailed investigations relating to individual factors are therefore conveniently handled with the OFAT approach.
2. ***OFAT data collection typically allows for immediate viewing and interpretation of the results.*** Most wind tunnels currently include computer software that can produce data plots of the results either in real time (i.e. point by point) or immediately upon completion of an individual OFAT sweep through a range of test points. Depending on the operational procedures for the particular wind tunnel, this may allow test engineers the ability to quickly alter subsequent test runs based upon prior run results.
3. ***OFAT testing is better understood and the results are often more readily accepted by researchers used to working with wind tunnel data.*** The OFAT approach is often used in wind tunnels at NASA Langley and many other academic and commercial facilities for decades – and is therefore the default preference for many researchers.

B. OFAT Testing Cons:

1. ***The presence of any unknown systematic errors present during the test will be incorporated into the data and cannot be corrected by post-processing after the test measurements are taken.*** Uncharacterized drifting of sensors or test apparatus settings would be examples of this type of error. Considerable time is spent at some wind tunnel facilities attempting to identify and characterize sources of systematic errors – after which they become "known" sources of bias or variance.
2. ***Known sources of bias and variance (nuisance errors) such as variability among operators, testing on different days or times of day with large temperature differences, etc., can add to measurement errors.*** Test engineers typically attempt to minimize these contributions through various testing strategies and procedures. Always approaching an angle of attack setting from a particular direction to minimize certain components of angle position error and aerodynamic hysteresis would be an example of this.
3. ***Repeat runs in an OFAT test are not statistically guaranteed to improve the modeling process.*** Repeat runs during OFAT testing are usually made to detect hysteresis or to check that the mechanical machinery and sensors associated with the wind tunnel and test article are working "close" to what they did during an earlier run – which may have been an hour earlier, the prior day, or as part of a prior wind tunnel test. Since the errors described in the previous two paragraphs are included in any repeated measurements (particularly if the repeats are taken sequentially or in close proximity to the original points), the repeated measurements may lead to incorrect conclusions about the resulting models and/or the fidelity of the test machinery.
4. ***Test times increase geometrically for cases where many factors are involved, making OFAT testing impractical for complex vehicles with significant factor interactions.*** Designing OFAT experiments to adequately capture the dependencies on a large number of factors (independent variables) as well as their interaction effects can be extremely difficult. An OFAT test with only 3 test points (high, low, and mid) to cover the range of each factor, would require 3^k test points to cover all the possible interactions. ("k" is the number of factors or independent variables.) As shown in Fig. 1b the LA-8 airframe had a total of 23

independent variables for the wind tunnel testing done to date (8 motor RPMs, 2 wing angles, 4 elevon deflections, 2 ruddervator deflections, 4 flap deflections, angle of attack, angle of sideslip, and dynamic pressure). At 5 seconds per point, 3^{23} test points would take 14,926 years (running 24 hours per day, 365 days per year). Making good engineering judgements based on symmetry, proximity of particular control effectors, etc. can significantly reduce the number of OFAT test points – but this may still result in unreasonable test times for a VTOL vehicle like the LA-8. Using assumptions about left/right symmetry, and ganging motors together one could potentially reduce the number of independent variables to about 12 for LA-8 – although you would have to double the result to test symmetric and antisymmetric control effectors. The resulting $2*3^{12}$ test points would still take over 200 days of OFAT testing (assuming 5000 points per day) – while only sweeping through 3 values to cover the range for each individual factor.

C. DOE Testing Pros:

1. ***The DOE approach provides run-efficient designs and adds statistical rigor to the initial wind tunnel test design process, to the acquisition of data, and in the final data analysis.*** During the wind tunnel test design process, test points are selected to (1) orthogonalize regressors that improve modeling, (2) reflect the desired levels of model fidelity required, (3) minimize certain criteria such as prediction errors, and (4) provide adequate statistical power to the test. During execution of a wind tunnel test, various modeling statistics, including fit errors and prediction errors, can be monitored.
2. ***Unknown systematic errors are addressed and mitigated in the DOE approach by randomizing the test matrix.*** Randomization prevents time-varying systematic errors from directly adding into the measurements and instead "transfers" the errors into a component of the measurement variance. In other words, estimated model parameters will not be corrupted, but the estimated parameter uncertainties will increase. For OFAT testing, estimated model parameters have a significant risk of being biased due to non-stationary systematic error – whereas those same errors will show up as higher parameter uncertainties in DOE testing.
3. ***Replication is used in a DOE design to allow assessment of pure error. Pure error and lack of fit are two sources of error that together define the total measurement error.*** A lack-of-fit test is commonly performed in a regression analysis of variance (ANOVA) table to determine if the estimated model presents a statistically significant lack of fit.
4. ***The DOE body of theory provides a broad range of approaches/options for many different experimental situations.*** "Screening" has not been used in the LA-8 study, but it is a DOE approach used to quickly determine important factors when those factors are not obvious to subject matter experts. This is likely to become increasingly important for complex VTOL vehicles like the LA-8 for which there is not a historical database of knowledge about what control effector interactions are important – or what the transitional concept of operations (CONOPS) should be.
5. ***The DOE approach's testing efficiency allows for characterization of responses and interaction effects for test articles with large numbers of independent variables that would be impossible to obtain using the OFAT approach.*** Simple calculations show that with even a modest number of factors with interactions present can result in OFAT test times quickly approaching years to accomplish. The LA-8 test had 23 factors. The GL-10 wind tunnel test had 29 factors – and there are other distributed electric propulsion configurations that have even more (e.g. some designs include collective and cyclic blade pitch for each propeller blade). As noted earlier, engineering judgement can be used to reduce the number of independent variables enough to provide some results from OFAT testing, but the danger is that you may miss some critical interaction – whereas DOE methods can capture all the interactions and identify those that are statistically significant.

D. DOE Testing Cons:

1. ***The wind tunnel facility hardware and control software must be capable of setting the successive random values of tunnel and airframe independent variables required by DOE testing – including things like angle of attack, angle of sideslip, control surface deflections, and motor RPMs.*** For both the GL-10 and LA-8 wind tunnel tests in the 12-Foot Tunnel, the dynamic pressure was held constant for each DOE run – but between 22 and 28 other motor settings and control surface positions were changed between each static test data point. Since OFAT testing has generally been the default methodology used in wind tunnels, many facilities are not currently set up to easily implement DOE testing.
2. ***DOE wind tunnel testing generally puts more short term "wear and tear" on the facility and airframe hardware on a point-by-point basis.*** DOE makes relatively larger changes in angle of attack, angle of sideslip, control surface deflections, and motor RPM values between successive test points – subjecting the related hardware to higher transient stresses compared to the smaller incremental changes between test points

typically seen in OFAT testing. There are certain cases, however, where DOE testing can produce less stress on certain components. This could occur if an OFAT test run holds motor RPMs or control surface servos at higher values for longer periods (multiple successive test points) than a corresponding DOE run. If the motors or servos are operating near or above their continuous rated capacity, then the OFAT runs may produce more component failures than the DOE runs, where higher values are typically held for shorter periods (less successive test points). Facility model support hardware (stings, turntables, etc.) making larger and more rapid changes in angle of attack and sideslip angle will almost certainly see more wear and tear from DOE testing – and this should be assessed for particular facilities considering the use of DOE testing.

3. ***DOE and flight dynamics subject matter experts are required to set up and generate DOE wind tunnel test schedules - and to interpret DOE wind tunnel test results after test data has been gathered.*** The availability of such subject matter experts may impact whether performing a DOE test is even possible.
4. ***DOE wind tunnel testing at many facilities does not currently allow for physical insight into (and interpretation of) the data as it is collected.*** Software at many wind tunnel facilities does not allow for plotting of DOE run results (forces, moments, coefficients, etc.) in a form comparable to what can be done for OFAT testing. DOE testing ultimately provides the same information as OFAT testing but requires an extra modeling step to extract equivalent information. If DOE testing becomes used more frequently, then the ability to look at the results after each DOE run in a more understandable way will become more available. There is a research and development effort called Rapid Aero Modeling (RAM) focused on closing the loop around wind tunnel testing and computational studies so that the results of individual DOE runs are used to guide and set parameters for subsequent runs to achieve desired levels of modeling fidelity – and would also provide the test engineers more immediate feedback about the test results. References [10] and [11] cover recent work in this area.

E. Combining OFAT and DOE Wind Tunnel Testing Approaches

A well thought out wind tunnel test can combine the best features of both the traditional OFAT and DOE testing approaches. The OFAT approach can initially be used to:

1. ***Get a broad understanding of the vehicle's response features.*** For a VTOL vehicle this might include doing enough OFAT testing to answer the following questions: Does the vehicle have adequate thrust and control authority in the different axes? Can the vehicle be trimmed in pitch going from a dynamic pressure of 0 (hover) up to dynamic pressures (speeds) consistent with forward flight? What are the vehicle's stability and control characteristics?
2. ***Define the ranges for individual factors (independent variables) appropriate for each portion of the flight envelope to be covered by particular DOE runs.*** For example, vehicle angle of attack, wing angle, and motor RPM ranges can be limited for subsequent DOE runs at a particular dynamic pressure to a range where the vehicle could maintain trimmed forward flight at a constant airspeed and altitude (quasi steady state transition points) – or for the vehicle accelerating in forward speed and altitude while remaining trimmed in pitch (representing a climbing out and accelerating transition between hover and forward flight). How this was done for the LA-8 testing is described in Sec. V.

IV. Lessons Learned from Static GL-10 DOE Wind Tunnel Testing in 2013

A. Recording of individual motor actual RPMs at each test point is necessary. Commercially available RC hobbyist hardware has become sophisticated enough in recent years to allow for frequent use in subscale airframes for flight or wind tunnel testing. These systems typically use pulse-width-modulated (PWM) control signals. The actual RPM resulting from a particular PWM command will change based on the loading on the prop/motor at particular test points – and also because the performance characteristics (as determined by a motor calibration run) can change over the course of just a few hours of continuous running in the tunnel. (This is particularly true if the motors are running at or near their maximum continuous rating.)

B. Testing at multiple dynamic pressure settings is necessary to realistically assess transition performance between hover and forward flight. The increased importance of propulsion effects and propulsion-airframe interactions for VTOL configurations like the GL-10 and LA-8 requires testing the vehicle at multiple dynamic pressures due to the different scaling parameters required for different vehicle components. For example, airframe components scale with freestream dynamic pressure, whereas propeller aerodynamics scale proportional to the local dynamic pressures experienced by individual propeller blades.

C. Trying to understand and model a complicated blown-tilt-wing configuration based only on data for the full configuration is very difficult. Having individual propeller/motor performance data and bare airframe data can greatly facilitate developing a usable model – although implementing a traditional "buildup" approach to aerodynamic modeling may not be well-suited for certain airframe configurations like the GL-10 and LA-8. This is discussed more fully in Sec. IV.

D. Averaging 10 seconds of static data (the historical default for the 12-Foot Tunnel) is not necessary. Results were just as good when data was taken/averaged over 2 seconds for each test point (Ref. [12]). To be conservative data was taken for 3 seconds per point after a 2-second settling time.

V. Initial OFAT LA-8 Wind Tunnel Testing in the Spring of 2019

A significant number of OFAT test runs previously defined by the LA-8 team were made for particular parts of the flight regime from hover to forward flight mode. Early test results raised some questions about the longitudinal stability of the airframe and where the airframe center of gravity (CG) ideally should be located. The airframe was also significantly heavier than originally designed, which prompted the test engineer to change the overall test plan and pursue a procedure that would answer the following questions:

- Can the LA-8 airframe produce adequate lift and thrust to fly at all dynamic pressures (forward velocities) between hover and wings-level forward flight?
- Can the LA-8 airframe be trimmed in the longitudinal axis at all the dynamic pressures between hover and wings-level forward flight?
- Does the LA-8 airframe have sufficient control authority throughout the hover-to-forward-flight transition?
- What wing angles, thrust settings, control surface settings, and concept-of-operations will allow the previous questions to be answered with a "yes"?

Initial hover testing with the tunnel dynamic pressure at zero indicated that a stationary hover could be achieved with both wings set to approximately 82°. Wing angles higher than 82° produced a net force in aft direction due to the blown-wing aerodynamics. Wing angles less than 82° produced a net force in the forward direction due to propeller thrust in the forward direction exceeding the aft component of the blown wing aerodynamic force.

For a tunnel airstream dynamic pressure of 0.50 pounds per square foot (psf) both wings were swept from 85° down to 0° and the propeller thrust on both wings was adjusted until the normal (vertical) force seen by the strain gage balance matched the predicted vehicle flight weight of about 60 pounds, and the axial force was approximately zero. These condition were satisfied with both wings at an angle of 56°. Then the motor commands to the front and aft wing propellers were adjusted incrementally in opposite directions until the pitching moment coefficient (C_m) was near zero for a given CG location. (This front wing/aft wing differential thrust procedure is highlighted in Fig. 4 later in this section.)

Using the process just described, "trimmed" pitch points were determined at dynamic pressures of 0, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75, 3.00, 3.25, 3.5, 3.75, and 4.00 psf. At each trim point the wing angles (the same for both wings) and motor thrust settings were manually adjusted to determine the values required to have lift = weight, drag = forward thrust, and pitching moment = 0 with all other control surfaces set to their nominal zero positions. Table 1 lists the vehicle settings associated with each of these points. Motor RPM or thrust settings were not included because there were changes to the LA-8 motor and propeller configuration made after the initial OFAT testing. This is discussed in Sec. VII of this paper.

Table 1 Dynamic pressures, wing angles, and control surface settings for "trim" points through transition where normal force = flight weight, axial force = 0, and C_m = 0.

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

*Although wing angles at Q=3.75 psf are the same as at 3.5 psf, the motor thrust settings were different.

The settings summarized in Table 1 (plus the motor settings) were combined into a single semi-automatic test run where the dynamic pressure for the tunnel and all other independent parameter settings were changed between successive points. Figure 3 includes plots of normal force, axial force, and C_m as a function of the tunnel dynamic pressure (Q). Although the plot shows all negative C_m values, it was very easy to flip the C_m positive with very small differential motor thrust setting changes between the front and aft wings. This sensitivity was particularly evident at hover and the low dynamic pressures settings.

The vehicle angle of attack and sideslip were kept at zero for all the points. Note that the wings were still tilted at 14° for Q = 4 psf in Table 1, indicating that transition to the forward flight configuration is not quite complete. (Testing with wing angles at 0° is described later in this section.) Theoretically each point in Table 1 represents a steady-state non-accelerating condition that the LA-8 airframe could fly, showing that longitudinally trimmed flight should be possible from hover up to slow forward flight.

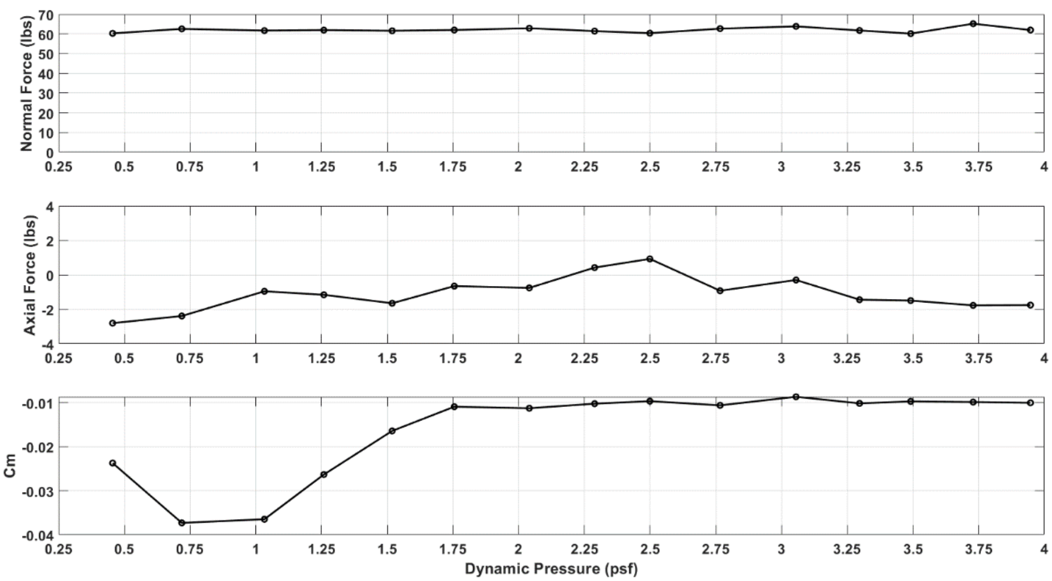


Fig. 3 LA-8 normal force, axial force, and C_m for "trim" points through transition.

Starting with the previously defined transition longitudinal trim points, additional sweeps were made to assess the adequacy of pitch, roll, and yaw control authority resulting from elevon, flap, ruddervator, and differential motor thrust settings. These sweeps included angle of attack ranging from -6° to +6° in 2° increments (trim points were taken at 0°). All four elevons were deflected antisymmetrically to roll right and roll left. To test pitch control authority, either the elevons on the front and aft wings were actuated in opposite directions or the ruddervators were deflected together up and down. Yaw control authority was tested by moving both ruddervators to the left and then to the right. Flap deflections included all flaps on both wings at 10° and 20°, front wing flaps only at 10° and 20°, back wing flaps only at 10° and 20°, right hand (RH) flaps (both wings) at 10° and 20°, and left hand (LH) flaps (both wings) at 10° and 20°. Combinations of elevon, flap, and ruddervator control surfaces were not checked. Motor differential thrust variations included sweeping the front wing motors below and then above the pitch trim point thrust values – while doing the opposite on the back wing. All control surface and motor thrust variations were done at sideslip angles of 0° and 5°. Because of the time required to make these OFAT control authority assessment sweeps for LA-8, they were done at a smaller number of dynamic pressure settings than was used to establish the trimmed points defining a transition flight corridor.

Differential wing tilt angles between the forward and aft wings was not part of this control authority assessment because it had been shown to be relatively ineffective for pitch control in earlier runs. Some of the reasons for this are discussed in Sec. VI of this paper.

Figure 4 is an example of an OFAT LA-8 test run where all 8 motors (4 per wing) were initially set at identical thrust settings, and both wings were held at 0°. This produces a nose-down pitching moment. Decreasing the thrust on the front wing and increasing thrust on the aft wing makes the C_m even more negative, but increasing the thrust on the front wing (W1) and decreasing thrust on the aft wing (W2) allows the C_m to cross zero for all the variations of alpha and wing flaps that were also included in this run. The dynamic pressure for the data in Fig. 4 was 6 psf, which is the highest we were able to test the LA-8 airframe to in the 12-Foot Tunnel.

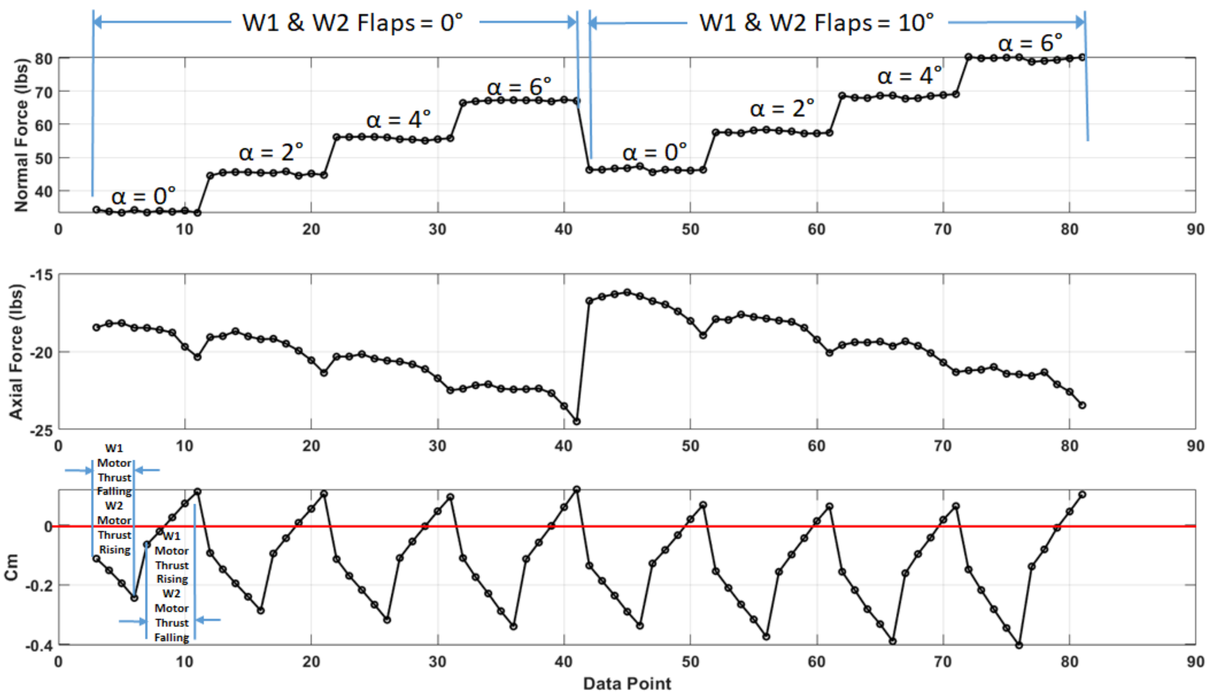


Fig. 4 OFAT run showing effectiveness of W1/W2 differential thrust for pitch control.

Near the end of the OFAT testing in the spring of 2019 another series of runs was made to roughly define the LA-8 major control effector settings for an accelerating climb-out transition corridor from hover to forward flight. The difference between this assessment and that described previously is that lift was set to exceed weight and thrust was set to exceed drag to match a condition where the vehicle in flight would be accelerating. (Pitching moment was still set to zero.) This was an initial assessment for a transition that might be more typical for UAM operations – whereas the prior steady-state "trim" settings would likely be closer to what is used during initial flight testing and flight envelope expansion. Table 2 includes all the vehicle settings obtained. Unlike the prior assessment, the settings for an accelerating climbout include the wings rotating all the way down to 0°.

Table 2 Dynamic pressures, alphas, wing angles and control surface settings for the LA-8 test run simulating an accelerating climbout.

Q	Alpha	Wing 1 Angle	Wing 2 Angle	Flap 1	Flap 2	Flap 3	Flap 4	All Four Elevons	Both Ruddervators
(psf)	(Deg)	(Deg)	(Deg)	(Deg)	(Deg)	(Deg)	(Deg)	(Deg)	(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

For lift to exceed or at least equal weight at the higher dynamic pressure settings, positive angle of attack and partial flap deflection were required. The normal force plot in Fig. 5 shows the lift exceeding weight for a good portion of transition. But in order to get the wing angles down to zero while maintaining enough lift eventually requires positive angle of attack and partial flap deployment. This reflects the fact that at its current weight, the nominal LA-8 cruising forward flight speed is higher than could be tested in the 12-Foot Tunnel.

The axial force plot shows a gradual buildup in force to about 25 pounds in the forward direction. An initial calculated estimate of the time required to execute this accelerating climbout yielded 18 seconds to go from hover to 4 psf (~40 kts), which seemed reasonable. Since the motor thrust settings were limited in the wind tunnel by the need to ensure the wind tunnel strain-gage balance did not get overloaded, this probably underestimates the performance LA-8 could achieve in actual flight testing.

The C_m plot shows small negative values near zero. As was noted in the discussion about Fig. 3, at hover and low dynamic pressures it only takes a small change in the relative motor thrust settings between the front and aft wings to make the C_m switch signs. There was sufficient pitch control power available to trim C_m to zero or drive it significantly positive or negative at any dynamic pressure settings tested. For all wind tunnel testing of the LA-8 the individual motor and control surface values for each test point were initially read from a text file table by the tunnel system software, which also generated the open loop commands to move the surfaces and drive the motors. (No closed loop controllers were used.)

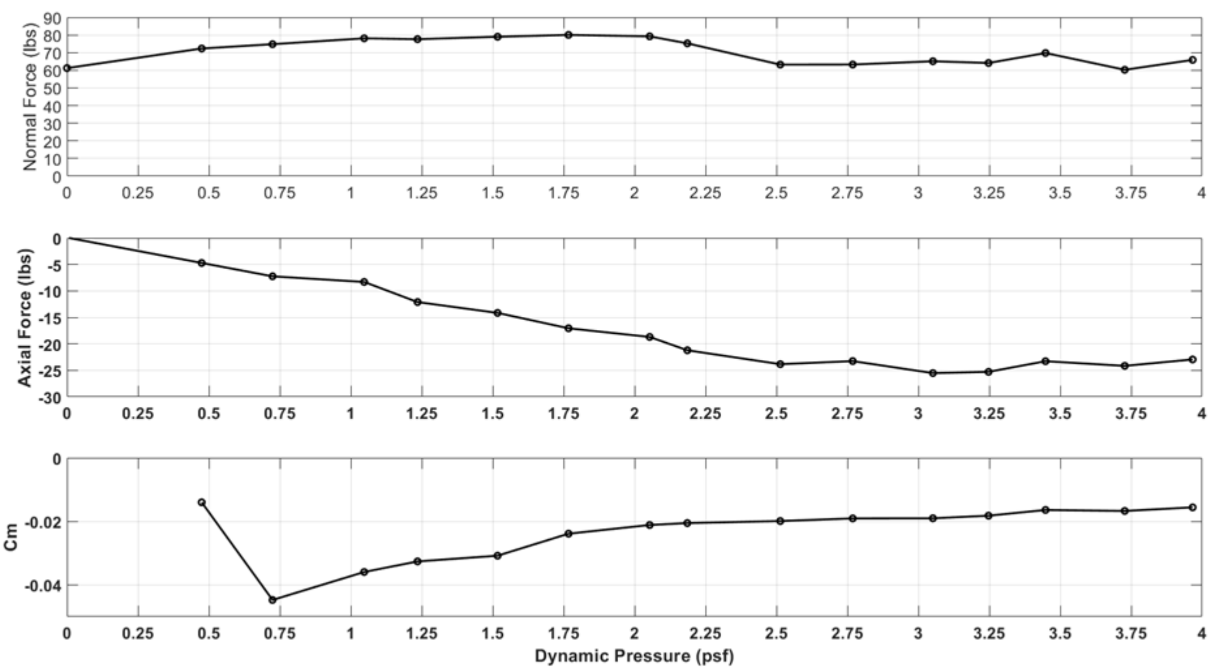


Fig. 5 Normal force, axial force, and C_m for LA-8 run simulating accelerating climbout.

A primary reason for attempting to determine independent parameter settings defining potential transition corridors was to establish ranges to be used in the planned subsequent DOE testing. Unlike the GL-10 DOE wind tunnel test where the full range for each control effector was tested at a dynamic pressure of 3.2 psf, the LA-8 control effector ranges for each test dynamic pressure were limited to values that are practical for that portion of flight envelope. For example, the wing angle range for DOE hover testing was 75 to 95 degrees (non-translating hover required the wings to be set between 82 and 85 degrees) – and for forward flight the wings were both locked at zero degrees. The ranges for the wing angles and control surface position were set primarily by the level flight pitch trim assessment – with some margin to provide overlap. For the motors, a somewhat higher range was generally used to allow assessment of the impact of losing particular motors. (For the hover DOE runs the range was 1900 to 6500 RPM.)

Detailed descriptions and extensive data plots for the spring OFAT testing are included in Ref. [4].

VI. Understanding LA-8's Pitching Moment Characteristics, Stability, and Control Options

Previous wind tunnel and flight testing of the GL-10 configuration identified some unusual pitching moment characteristics, with the vehicle undergoing at least one noticeable reversal in the pitching moment direction as it transitioned from hover to forward flight. GL-10 had a tilt-wing with eight electrically driven propellers and a tilt-tail with two additional propellers, which gives it a number of similarities to the LA-8 configuration (reference Fig. 2). Although the OFAT testing summarized in Sec. V established that the LA-8 airframe could be trimmed in pitch throughout a transition from hover to forward flight, some of the pitching moment characteristics were "unusual" in comparison to conventional airplanes. The following figures and accompanying discussion are an attempt get an initial understanding of the physics and fundamental aerodynamics that might account for those characteristics.

The locations of aerodynamic centers, wing rotation points, the vehicle overall CG, and all distances shown are approximate, but they are close enough to help illustrate why certain changes occur through transition flight. This section will describe and discuss: 1) how the different forces produce pitching moment increments, 2) how those increments change as the vehicle transitions from hover to forward flight, 3) why differential wing tilt is less effective and predictable for controlling pitch than differential thrust between the front and aft wing propellers, and 4) how a nose-down fuselage attitude from hover through most of the transition may provide better pitch control and less wing-to-wing interaction than a nose-up fuselage attitude.

Figure 6 shows a simplified version of the aerodynamic forces acting on the LA-8 airframe in hover with no forward velocity. Propeller thrust includes a forward-facing component that just offsets the aft-facing component of the blown-wing aerodynamic forces. For the front wing (Wing 1) the propeller thrust acting about the CG produces a nose-up (positive) pitching moment, whereas the blown-wing aerodynamic force acting about the CG for the same wing produces a nose-down (negative) pitching moment. For the aft wing, (Wing 2) the directions of the pitching moments produced by the propeller thrust and the blown-wing aerodynamic force are again in the opposite directions – with each also being opposite the correspond component on the front wing.

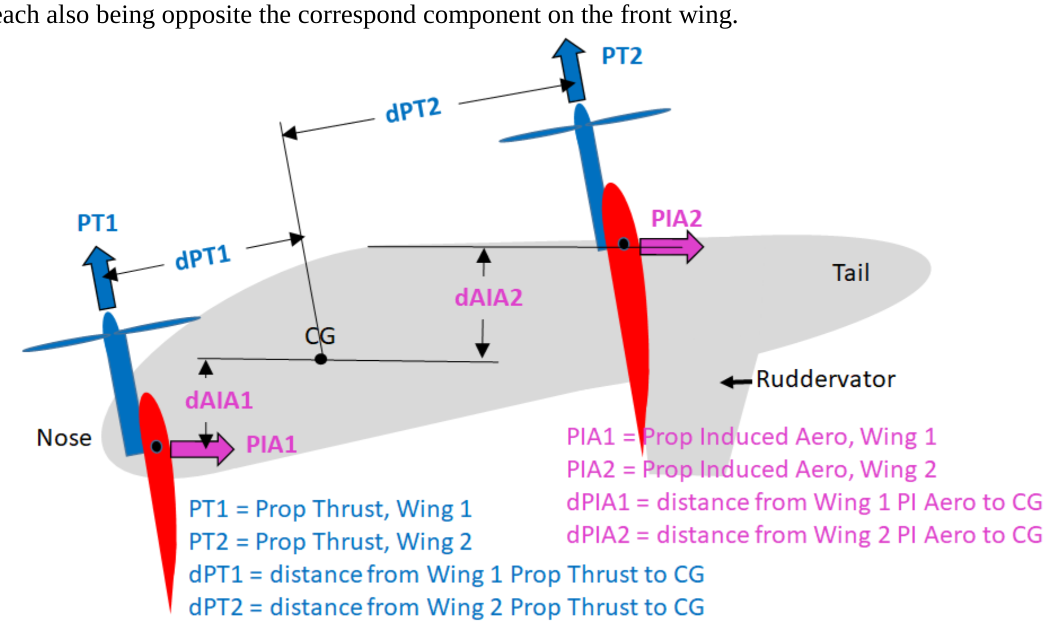


Fig. 6 LA-8 forces relative to CG while in hover mode (no forward velocity, wings at 82°).

Tilting an individual wing will therefore produce two incremental changes in pitching moment that will be opposite in direction. Determining the net effect of tilting a wing on the pitching moment then becomes a function of which combination of force magnitude and offset distance produces the larger incremental change.

Before any testing was done on LA-8 there was an assumption that differential wing tilt might be an effective method for controlling pitch attitude. Test sweeps to assess this showed far less control authority than expected. Figure 6 gives some indication why this may be true in hover, and additional figures will show how things get even more complicated as LA-8 transitions toward forward flight.

Figure 7 shows the forces relative to the vehicle CG for LA-8 roughly midway through transition. For discussion purposes the wing aerodynamic force induced directly by the propeller is shown separately from the wing aerodynamic force induced by the airstream. Both wings are at approximately 40° and the fuselage is nominally level (vehicle angle of attack = 0°). For this case the pitching moment increments due to the direct propeller thrust and the propeller induced aerodynamic forces are now in the same direction – not opposing each other like they were for the hover case. Somewhere between a wing angle of 82° and a wing angle of 40° the line of action for the propeller-induced aerodynamic forces for each wing passes through the CG, reversing the direction of the resulting pitching moment increment.

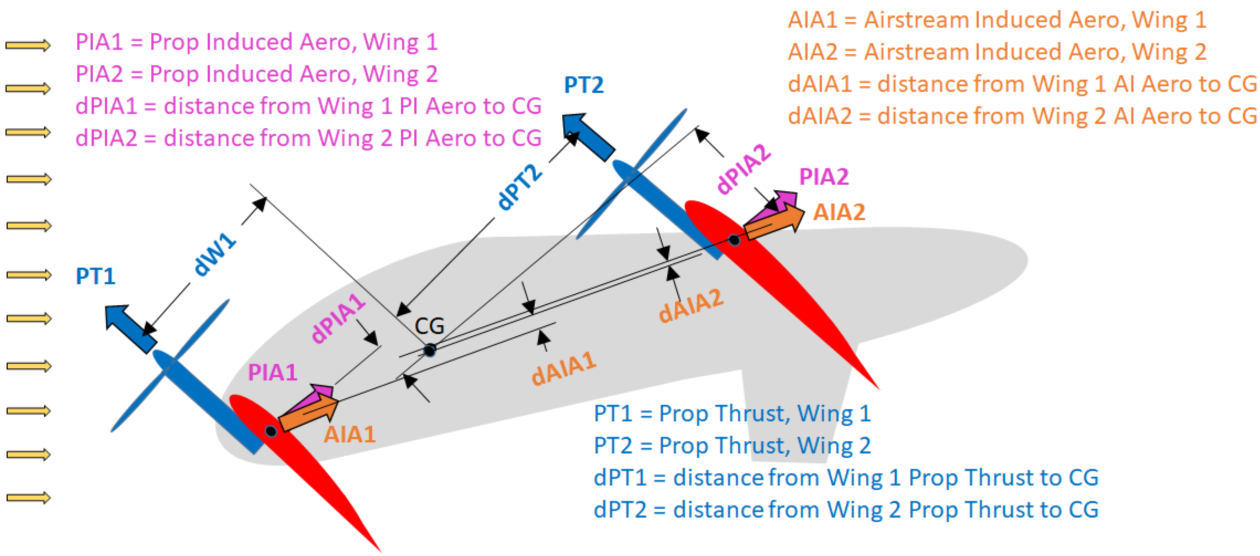


Fig. 7. LA-8 forces relative to CG while in transition mode (moderate forward velocity, wings at ~40°).

Although wing aerodynamic force components due to the airstream have relatively small moment arms as shown in Fig. 7, it is clear that these components will also produce a reversing increment of pitching moment as the wings rotate. Since the reversal of pitching moment increments would be expected occur at different wing angles for the front and aft wings, this will create a complicated changing character to the net pitching moment as the vehicle goes through transition between hover and forward flight.

Figure 8 shows LA-8 in the forward flight position with wings nominally zero and the fuselage at an angle of attack of 0°.

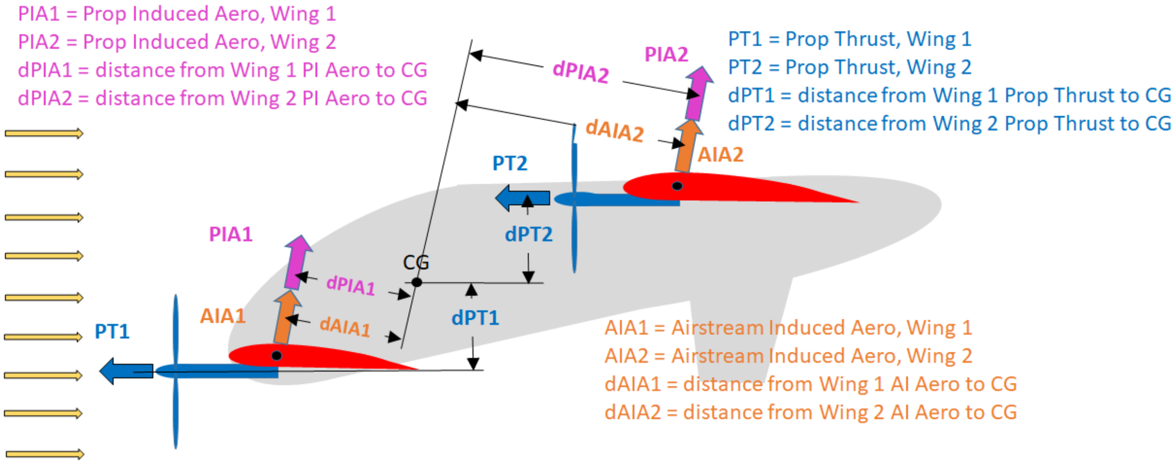
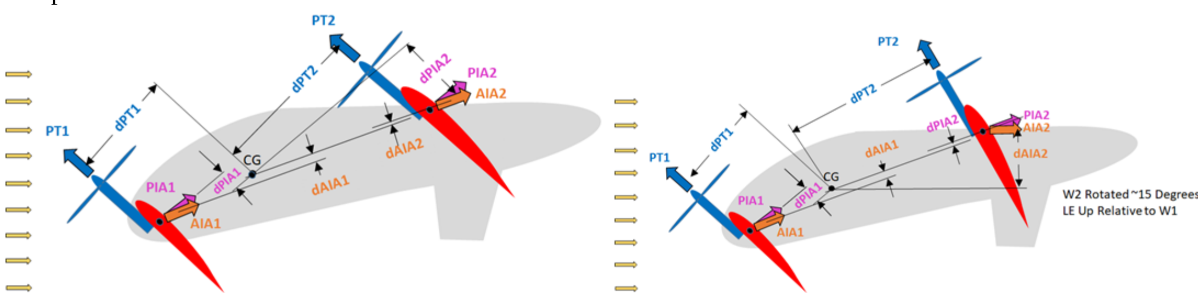


Fig. 8 LA-8 forces relative to CG while in forward flight mode (max forward velocity, wings at 0°).

In Fig. 8 the propeller thrust is aligned with the airstream so that the wing aerodynamic force components will be aligned. Front wing forces all act to produce a nose-up pitching moment, and aft wing forces all act to produce a nose-down pitching. If all 8 motors were run at the same thrust setting, then the expectation would be that the net pitching moment would be nose-down, since the aft wing has a larger area, the distance dPT2 is slightly larger than dPT1, and there is little difference between the incidence angles. This expectation was confirmed by the OFAT run previously shown in Fig. 4. Figure 4 data is from an OFAT run made after the vehicle configuration change described in the following section, so that all motors and propellers were identical and set to the same initial thrust settings. With all motors at the same thrust setting C_m was negative. To trim the aircraft, the front wing motors thrust setting had to be increased relative to the aft wing motors.

Figure 9a shows the LA-8 in a mid-transition position where both wings are tilted at approximately 40°. The moment arms for the aft wing are dPT2 for the propellers, dPIA2 for the propeller-induced component of wing aerodynamic forces, and dAIA2 for the airstream-induced aerodynamic forces. For the configuration in Fig. 9a PT2*dPT2, PIA2*dPIA2, and AIA2*dAIA2 all produce a nose-down pitching moment, although the last two component are small.



(a) Both wings at ~40° **(b) Aft wing rotated CW to ~55°**

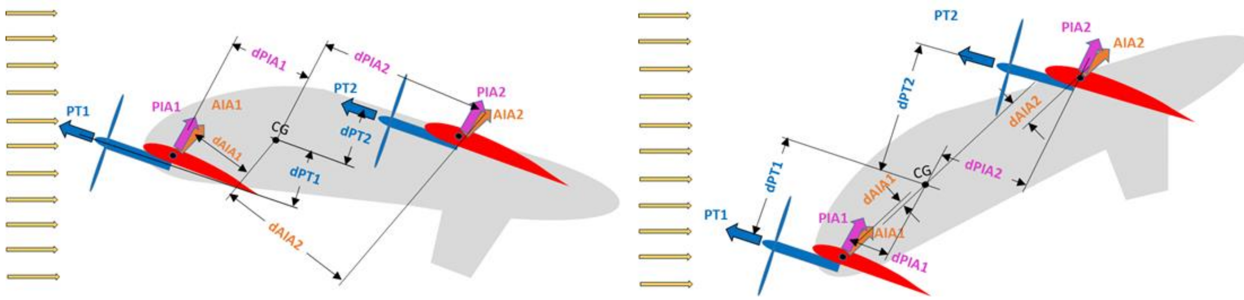
Fig. 9 Impact of wing tilt change on LA-8 forces relative to CG.

In Fig. 9b the aft wing has been rotated approximately 15° leading edge up relative to Fig. 9a. The changes in the aft wing (W2) moment arm lengths will slightly increase the nose down pitching moment due to W2 propeller thrust, reduce the W2 propeller-induced wing aerodynamic force contribution to nose pitching moment, and cause the airstream-induced wing aerodynamic forces to produce a nose-up pitching moment.

Changing the wing tilt angle of either wing can produce incremental changes to the pitching moment about the CG in different directions – depending on which forces are being considered and what the particular values are for forward velocity, propeller thrust, wing tilt angle, and the vehicle angle of attack.

Differential wing tilt was the method originally proposed for controlling pitching moment for LA-8. OFAT testing in the spring of 2019 indicated that using differential wing tilt as a method for controlling pitching moment was not as effective or as predictable as originally expected. This was identified early on in the test, and alternate approaches for controlling pitch attitude were investigated. Keeping both wings at the same tilt angle and using differential propeller thrust from the front and aft wings produced far better control authority and was much more predictable – since the direction of the pitching moment change remains constant throughout the transition between hover and forward flight.

VTOL configurations that undergo geometric changes like LA-8 can present additional options for how transitioning between hover and forward flight is accomplished. Figure 10a shows LA-8 with both wings rotated fully down to their forward flight positions, but the fuselage angle of attack is relatively high. This could represent slow forward flight where the higher alpha is required to get adequate overall lift.



(a) Wings at 0°, vehicle AOA at +15° **(b) Wings at 30°, vehicle AOA at -15°**

Fig. 10 LA-8 forces relative to CG for different fuselage angles.

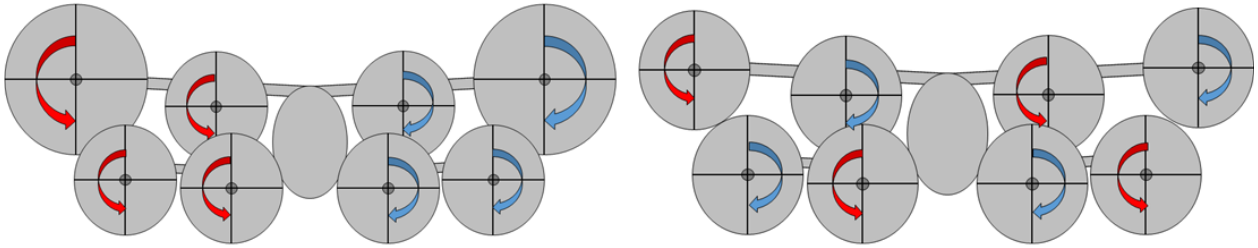
Figure 10b shows LA-8 with the wings at the same angle relative to the airstream as the left side, but the fuselage has been angled nose down. If the thrust settings are the same for both configurations, then we would expect both configurations to produce about the same wing lift. The following possibilities may warrant further investigation:

- The configuration on the right has longer moment arms from the propeller thrust to the CG, which may provide for better pitch control.
- The configuration on the right will probably have less adverse interactions between the front and aft wings. (The configuration on the left looks like shed vortices and unsteady wake effects from the front wing may directly impact the aft wing.
- The previous potential benefits would have to be weighed against the reduce fuselage lift and higher fuselage drag the configuration on the right would produce.

In this section the figures and discussion imply that the LA-8 overall vehicle CG location is constant. In reality the overall vehicle CG location sweeps through an arc as the wings rotate from vertical to horizontal. For wings vertical the overall CG is approximately 1.1 inches aft and 1.1 inches higher than when the wings are horizontal in the forward flight configuration. (See Ref. [4] for a more detailed discussion of the LA-8 mass property changes associated with the tilting wings.) The overall vehicle CG location change is small relative to the aerodynamic force reorientation and distance changes, so it was not deemed important enough to include in the previous discussion. However, it should be noted that the amount of CG shift associated with wing tilting could be significantly higher for other tilt-wing vehicles, depending of the wing rotation points in relation to the wings' mass distributions. Although small, this CG shifting is another factor that further complicates the physics of the pitching moment changes as LA-8 transitions between hover and forward flight.

VII. LA-8 Configuration Changes Made After the Spring 2019 OFAT Testing

Figure 11a is a front view of the LA-8 configuration that shows the propeller configuration originally installed and tested during the OFAT wind tunnel entry in the spring of 2019. All eight tractor propellers were located ahead of leading edge of the wings to which they are mounted. The six smaller units were 3-bladed folding propellers, and the aft wing (W2) tip propellers were larger non-folding propellers mounted on bigger motors than the other six. The original intent was that the aft wing tip motors and propellers would be used for cruise flight, and all the other propellers would be shut down and folded back. All propellers on the left-hand side of the airframe rotated clockwise (CW) as seen from the front, and all propellers on the right-hand side rotated counter-clockwise (CCW). The smaller-diameter CCW propellers were custom-made. All the other propellers were commercial off-the-shelf (COTS) items.



(a) Spring of 2019 OFAT test configuration **(b) Summer of 2019 DOE test to present configuration**

Fig. 11 Front view showing LA-8 motor and propeller configurations.

Early testing revealed the following issues with the 11a configuration: 1) the custom-made folding CCW propellers produced noticeably less thrust than the COTS CW folding propellers at identical RPMs, 2) the blade pitch on the larger non-folding aft wing tip propellers was too shallow to produce thrust at the higher vehicle velocities required for cruising forward flight, and 3) a wings level forward flight configuration with equal thrust on all eight propellers produces a vehicle net nose-down pitching moment, indicating that front wing motors might be better for cruise flight. (Using two front wing motors for cruise will tend to counteract the vehicle's nose-down pitching moment, whereas using two aft wing motors would increase the nose-down moment that would have to be countered to maintain longitudinal trim. Reference Sec. VI.)

After considering the issues with the 11a configuration, a decision was made to: 1) replace the aft wing tip motors and propellers with ones identical to those at the other six locations, and 2) split the CW and CCW propellers evenly between the left-hand and right-hand sides of the airframe. This is the motor and propeller configuration shown in Fig. 11b and used for the summer 2019 powered DOE testing, The 11b configuration simplifies the assessment of the subsequent wind tunnel test results, and allows for any subset of the propellers to be used for cruise forward flight.

VIII. Powered DOE Wind Tunnel Testing of LA-8 in the Summer of 2019

During August and September of 2019 a DOE test of the LA-8 airframe was completed in the 12-Foot Low-Speed Wind Tunnel. All eight motors were the same type, and folding propellers of the same diameter were used at all eight locations. Sets of DOE run blocks were completed at dynamic pressures of 0, 0.5, 1.0, 1.5, 2.5, 3.5, 4.5, and 5.0 psf. All planned DOE testing was successfully completed with the exception of several runs which had to be conducted with elevons locked out due to burned out servos. Details of how the data from this test was assessed and used in development of aerodynamic models is described in Ref. [6]

Comments highlighting particular aspects of the powered LA-8 DOE testing:

1. ***At each dynamic pressure tested, the ranges for wing angles and all the control surfaces were limited to values appropriate for the portions of the flight envelope corresponding to that dynamic pressure.*** This was already discussed in Sec. V in relation to the OFAT testing, but it bears repeating to state that for the LA-8 DOE testing the data was taken only for component settings that are inside the vehicle's nominal flight envelope. This was not true for DOE testing of GL-10 in 2013, which did include taking data for the full range of all variables at all dynamic pressures tested. Limiting the LA-8 independent variable ranges based on the projected transition envelope obtained from the OFAT "trim" point studies was a major improvement in the wind tunnel testing efficiency in comparison to the GL-10 testing. Table 3 lists the independent variable setting ranges that were applied to each of the dynamic pressures included in the LA-8 DOE testing. Although flaps, elevons, ruddervators, and motors are listed together in the table, each individual control effector was treated as an independent test factor. (Although outside the range of normal flight operations, allowing all individual motor RPMs to drop to idle allowed for the resulting aerodynamic models to include an initial estimate of the impact of losing any motor or combination of motors.)

Table 3 Independent variable ranges for each dynamic pressure for the LA-8 powered DOE test.

Q	Alpha	Beta	Wing 1 Angle	Wing 2 Angle	All Four Flaps	All Four Elevons	Both Ruddervators	All Eight Motors
(PSF)	(Deg)	(Deg)	(Deg)	(Deg)	(Deg)	(Deg)	(Deg)	(RPM)
0	-9.9 to +15	-5 to +5	75 to 95	75 to 95	0 to 40	-25 to +25	-30 to +30	1900 to 6500 *
0.5	-9.9 to +15	-5 to +5	45 to 85	45 to 85	0 to 40	-25 to +25	-30 to +30	1900 to 6500 *
1.0	-9.9 to +15	-5 to +5	35 to 55	35 to 55	0 to 40	-25 to +25	-30 to +30	1900 to 6500 *
1.5	-8 to +8	-5 to +5	25 to 45	25 to 45	0 to 20	-25 to +25	-30 to +30	1900 to 6500 *
2.5	-6 to +6	-5 to +5	0 to 35	0 to 35	0 to 20	-25 to +25	-30 to +30	1900 to 6500 *
3.5	-6 to +6	-5 to +5	0 to 25	0 to 25	0 to 20	-25 to +25	-30 to +30	1900 to 6500 *
4.5	-6 to +6	-5 to +5	0 to 15	0 to 15	0 to 20	-25 to +25**	-30 to +30	1900 to 6500 *
5.0	-6 to +6	-5 to +5	0	0	0 to 20	-25 to +25**	-30 to +30	1900 to 6500 *

*Motor lower limit set to slow idle. Motor upper limit determined by strain gage balance loading limits.
** Burnt-out elevon servos required the elevon deflection angles to be set to zero at Q = 4.5 and 5.0 psf

Figure 12 shows in gray the LA-8 Table 3 DOE wing angle range as a function of dynamic pressure. The Table 1 steady-state trim points and the Table 2 accelerating climbout trim points are also plotted. This figure demonstrates how the OFAT testing results were used to define DOE test ranges for critical independent variables.

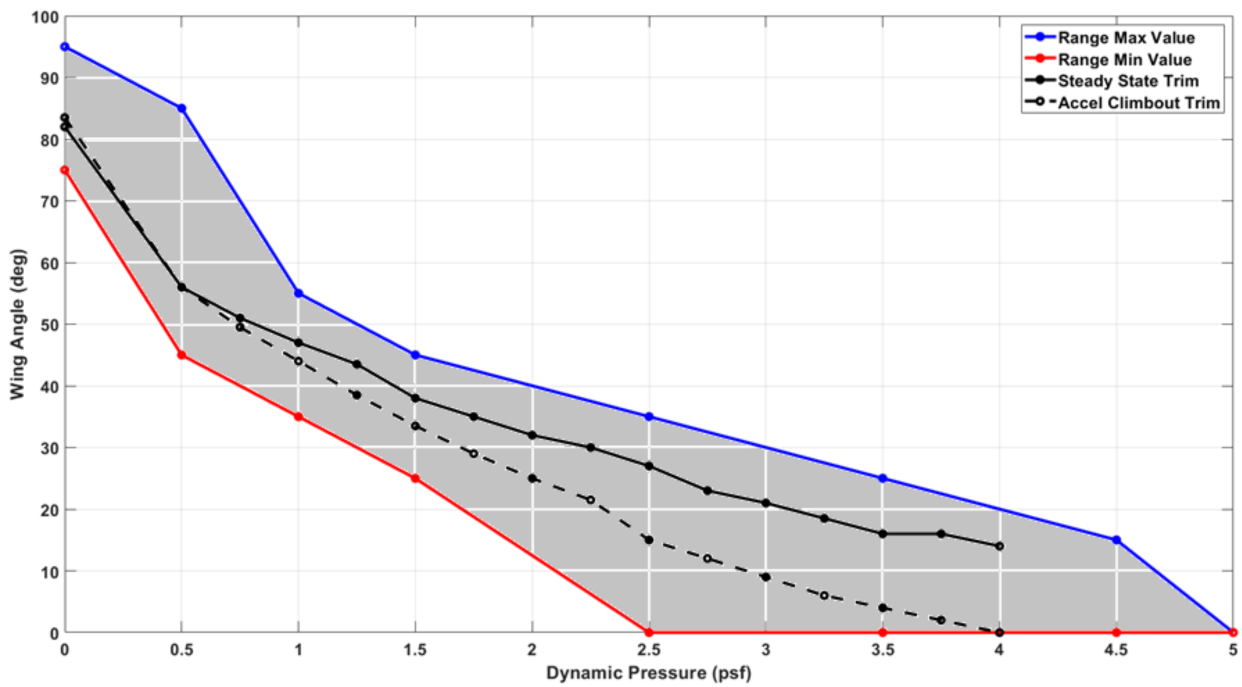


Fig. 12 LA-8 OFAT trim point wing angles and DOE wing angle range limits.

2. ***The test point settings for independent variables generally cover the entire ranges for that DOE run block – and not just the endpoints and middle values.*** Based on prior discussions about DOE with other researchers, it is evident that there is a misconception of only testing at the end points and middle of the range for each factor. This is not the case. There are many options for experiment design. For the LA-8 DOE tests, designs were based on concepts being considered for the Rapid Aero Modeling (RAM) approach described in [10]. The first block is a face-centered design (FCD), which explicitly ensures that endpoints are well-captured. The second block is a "nested FCD" block that combined with the initial FCD guarantees at least 5 points for each factor [13]. The third and fourth DOE blocks provide a significant number of additional optimized test points that minimize prediction error. For prior DOE wind tunnel tests at NASA Langley, the

entire range between the endpoints have typically been covered well when looking at all the data run blocks associated with a particular dynamic pressure. For example, during the GL-10 DOE wind tunnel test in 2013 the wing angles actually set/tested included points at about 2-degree increments for the entire range between 0 and 90 degrees. Figure 13 includes 2D plots showing the distribution of test points with a series of five DOE run blocks specified from RAM for a 22-factor experiment [7,8].

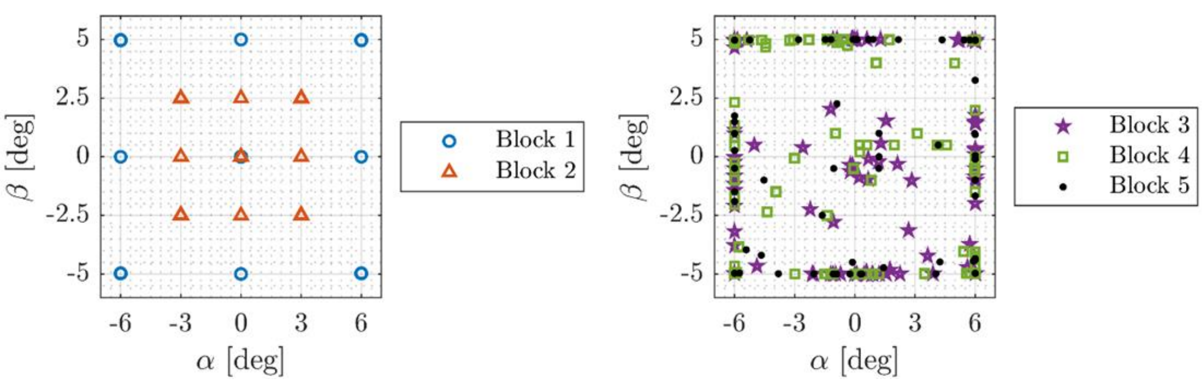


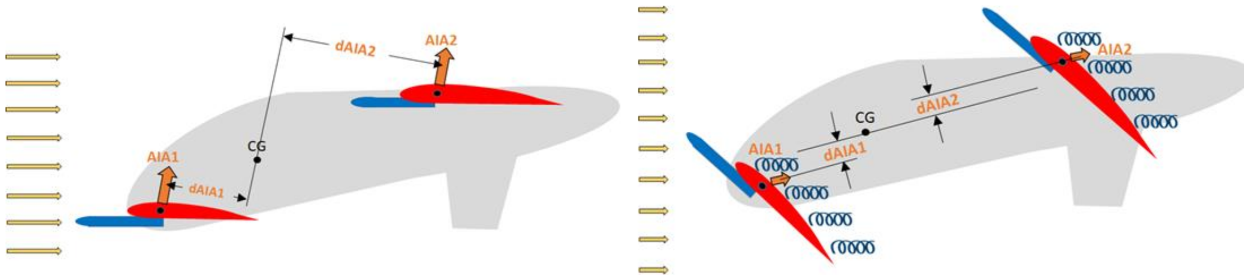
Fig. 13 2D plot showing the distribution of test points within a series of five RAM run blocks.

3. ***The resolution or "fine detail" of response characteristics and factor interactions is a function of data density – with DOE testing being able to achieve the same resolution as OFAT testing for a given data density.*** One concern or misconception is that DOE tests may not capture fine details at a particular test condition as well as an OFAT test. To make it easier to see why this is not the case, let's first consider a wind tunnel test run that is a single long OFAT sweep through angle of attack in 1° increments. This run could also be done with DOE techniques (such as randomizing the test point order, but taking the same number of test points) - and the DOE results would include information about errors that the OFAT run did not. The mathematical interpolation options available to estimate responses between data points would be equivalent for both methods, and the DOE data points in this case would be just as fine as the OFAT results with regard to resolution. However, in many cases DOE/RSM data is collected to ultimately fit models specifically because it is not practical to collect the data at as high a density as typical OFAT testing of all the independent variables would provide. Models generated from a lower density of data points will miss some of the fine detail, regardless of whether the collection techniques involved OFAT or DOE testing. For any subset of factors and a given number of test points the DOE approach should always be able to match or provide better resolution than can be achieved for the same number of test points taken using the OFAT approach. DOE/RSM simply provides a sequential process of adding data points, only as needed, to match the observed model complexity.

IX. Component Testing and Buildup Approach for Aerodynamic Modeling for LA-8

Past experience has shown that conducting bare airframe tests and combining the results with isolated propeller test results can produce reasonable aerodynamic models for conventional airplanes. Recent work testing quadcopters at NASA Langley indicates that this approach is also applicable to quadcopters [14].

Configurations like LA-8 present challenges for using the component testing and buildup approach. For example, Fig. 14 depicts the bare airframe aerodynamic forces acting on LA-8 in both the forward flight configuration and midway through transition. In the forward flight configuration the flow remains attached, resulting in typical airplane wing aerodynamic forces. As the wings are rotated up to transition from forward flight to hover, at some point each wing will stall, potentially not at the same angle. Figure 14b shows fully developed stall on both wings, and it is obvious that vortices being shed by the front wing will impact the flow field for the aft wing.



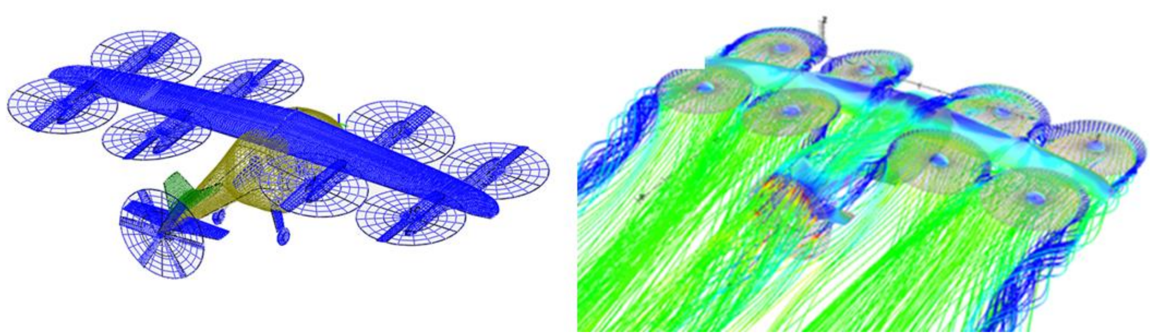
(a) Wings in forward flight configuration **(b) Wings at ~40° (transition flight configuration)**

Fig. 14 LA-8 aerodynamic forces for all motors off and props folded

Obtaining physics-based models for VTOL configurations that combine component testing results together is a worthwhile goal, particularly if it allows for configuration changes that produce accurate predictions even if that particular configuration has not been tested. However, the discussion in Sec. VI would suggest that using a buildup approach for initially developing an accurate aerodynamic model for LA-8 may be very difficult.

Isolated propeller testing of the LA-8 propellers was conducted in the 12-Foot Tunnel in January of 2020 [8], and bare airframe DOE testing was completed in February of 2020. Attempts were made to combine these test results with the powered LA-8 DOE test results from the summer of 2019. However, the best approaches were found to be either (1) to use only the powered airframe DOE data for model development, or (2) combine the isolated propeller models [9] with the powered airframe DOE data for model development, using the methods described in Ref. [8]. Bare airframe data was found to be challenging to superimpose with the isolated propeller and powered-airframe data, particularly in the transition flight regime.

Several of this paper's coauthors are involved with computational flow analysis of the Lift + Cruise VTOL configuration shown in Fig. 15. (See Ref. [11] for more details.) Figure 15b highlights the rotor wake interactions with the wing and tail during transition to horizontal flight. These interactions were found to be airspeed dependent and highly unpredictable, making the buildup approach very difficult to implement for this configuration.



(a) **(b)**

Fig. 15 Recent computational flow analysis image for the Lift + Cruise configuration.

Some of the new VTOL configurations currently being investigated by the aerospace community may allow the traditional component testing and buildup approach for aerodynamic modeling to be used successfully, but based on recent experience the authors of this paper would caution against assuming that the approach will work well for all VTOL configurations.

IX. Potential Issues With LA-8 Initial Hover Testing Results

The LA-8 2019 OFAT and DOE hover testing results need to be assessed carefully - keeping some of the limitations of the test facility in mind. Figure 16 is a cutaway of the NASA Langley 12-Foot Low-Speed Tunnel showing some of the major features of this facility. Reference [15] provides overview of dynamic test techniques used at NASA Langley Research Center on scale models to obtain a comprehensive flight dynamics characterization of aerospace vehicles – including testing in the 12-Foot Tunnel.

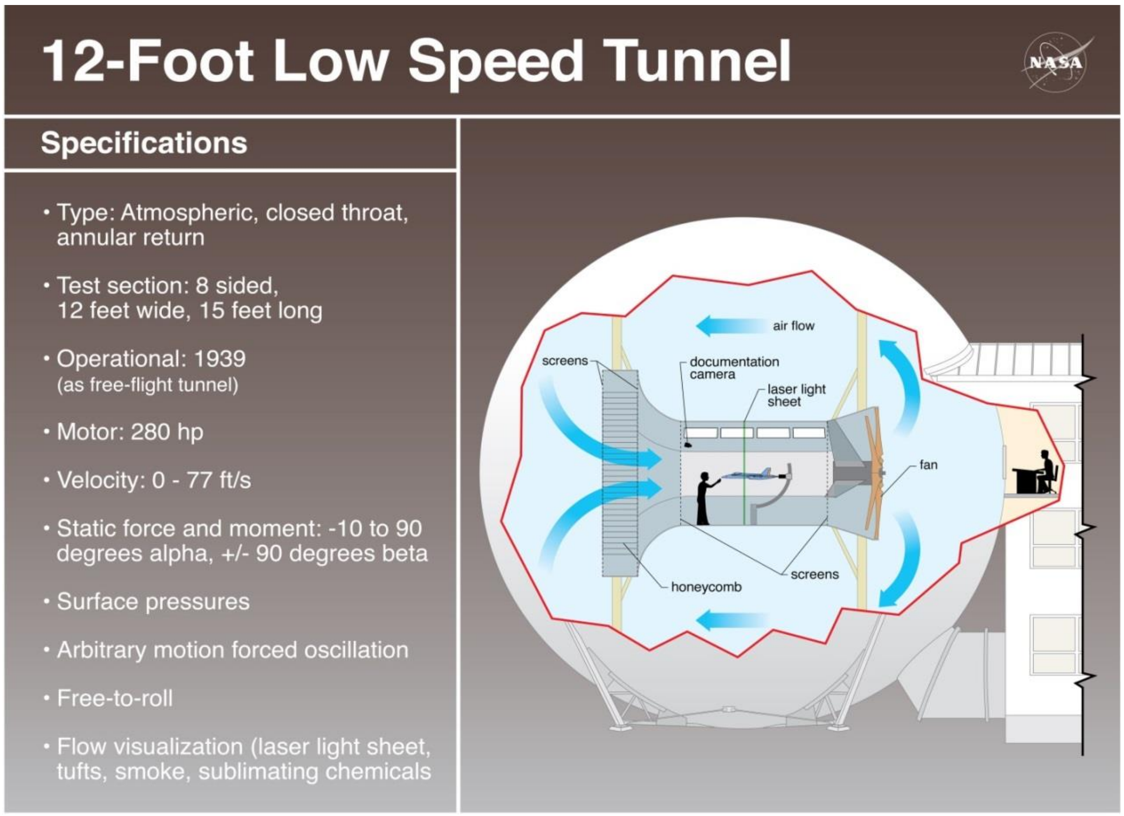
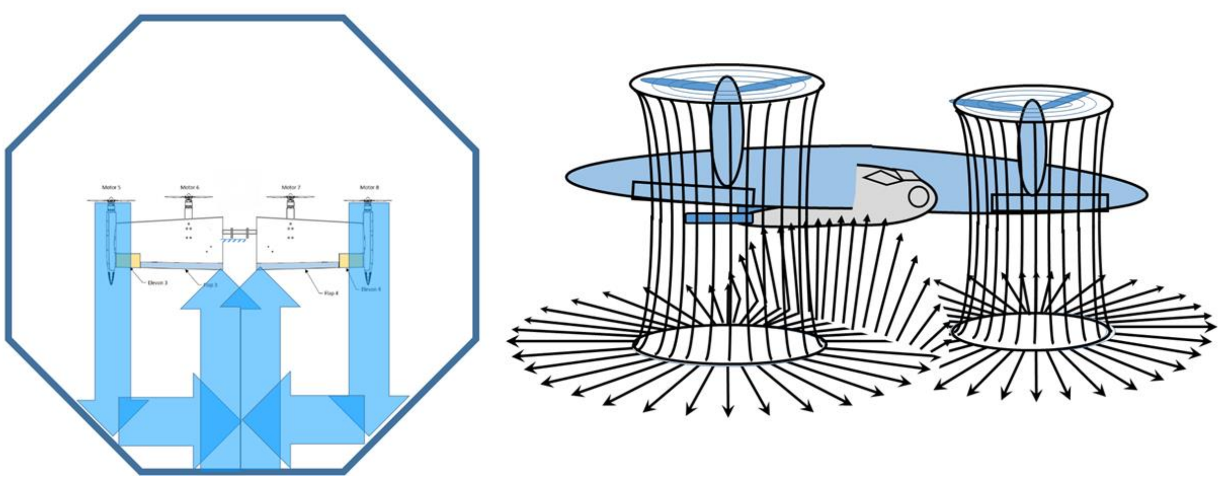


Fig. 16 Facility cutaway for the NASA Langley 12-Foot Low Speed Tunnel.

The LA-8 was mounted horizontally in the test section for all testing done to date. Therefore when the hover testing had the wings tilted between 80° and 90° the propeller flow was directed down toward the floor. Figure 17a shows a properly scaled LA-8 aft wing in the octagonal 12-Foot Tunnel test section as it was for the hover testing. Figure 17b shows a depiction of the flow field for a 2-rotor tilt wing vehicle operating in ground effect.



(a) **(b)**

Fig. 17 LA-8 potential hover testing issues.

Near the ground, tilt-wing VTOL configurations with multiple rotors or propellers can experience an increment of lift that is positive (i.e. if deflected flow from the ground pushes up on the fuselage), negative (i.e. if propeller flow creates a lower pressure area under the airframe), or neutral. The 2-rotor configuration in Fig. 17b is shown experiencing a positive lift increment. Assessing the impact of ground effect on a VTOL vehicle can be very important

– particularly for configurations where wind gusts or control oscillations can cause sudden changes to the effect by shifting how the flow gets deflected. In general, a larger number of lift rotors or propellers results in a reduction in the unsteady nature of the ground effect, which should be favorable for the LA-8 configuration.

However, LA-8 is relatively large compared to the 12-Foot Tunnel test section dimensions (Fig. 1a) – and the thrust produced by all the motors running at once will change the flow field in the test section. (In the forward flight configuration with wings level, running all the motors produces enough thrust to turn the tunnel fan blades when the tunnel drive motor is off.) As shown in Fig. 17a, the outboard propellers on LA-8 produce flow that will be deflected off the angled sides of the lower half of the test section. This will direct more of the flow back toward the center of the tunnel and limit the spreading out of the flow away from the vehicle. This may increase the positive ground effect and give a higher prediction for total lift than would be seen in a less confined test area.

Another potential consequence is that changes to the angle of attack or sideslip angle may produce unexpected interactions between components widely separated on the vehicle. For example, adding sideslip to the LA-8 configuration depicted in Fig. 17a will change the flow field asymmetrically. Relative to the vehicle centerline, the angled lower sections of the tunnel walls will deflect the flow from the propellers on one side of the vehicle slightly toward the front, and from the other side of the vehicle slightly toward the back. Instead of meeting at the same point in the middle of the tunnel and getting deflected upward there, the flows may pass by each other, hit the angled lower wall section on the opposite side of the tunnel, and then deflect up to interact with components on the opposite side of the vehicle from the propeller producing that flow. This potential complicates assessments of whether particular regressor terms should be included in the aerodynamic modeling. In still air the flow field under and around the hovering vehicle depicted in Fig. 17b will be the same regardless of the sideslip angle, whereas in the octagonal test section of the 12-Foot Tunnel changes in sideslip angle can produce real measureable effects.

The significance of the wall, floor, and ceiling effects on VTOL configuration testing in the 12-Foot Low-Speed Tunnel is an area for further investigation. As an initial step in this investigation, planned additional testing of LA-8 includes mounting the airframe both vertically and horizontally in the test section to compare the results obtained for hover testing. (If the LA-8 airframe is mounted vertically, the flow from the propellers will be directed along the normal flow path for the tunnel, thereby eliminating the impact of flow being deflected off the walls, floor or ceiling. Theoretically this should allow for hover testing that produces results more consistent with what would be seen at altitude (outside of ground effect).

X. Comparison of LA-8 OFAT and DOE Test Results, Planned Additional Testing

Although we cannot currently compare powered LA-8 DOE and OFAT results because of the motor and propeller configuration changes between the initial two wind tunnel tests, we can make some comparisons for the unpowered data. Figure 18 shows measured OFAT bare airframe data for C_L and C_D at Q = 4.5 psf with zero wing angle and zero control surface deflections as a function of α depicted using blue circles. The dashed red lines represent an RSM aerodynamic model developed from the February 2020 DOE bare airframe test data covering the same airframe configuration and tunnel test conditions.

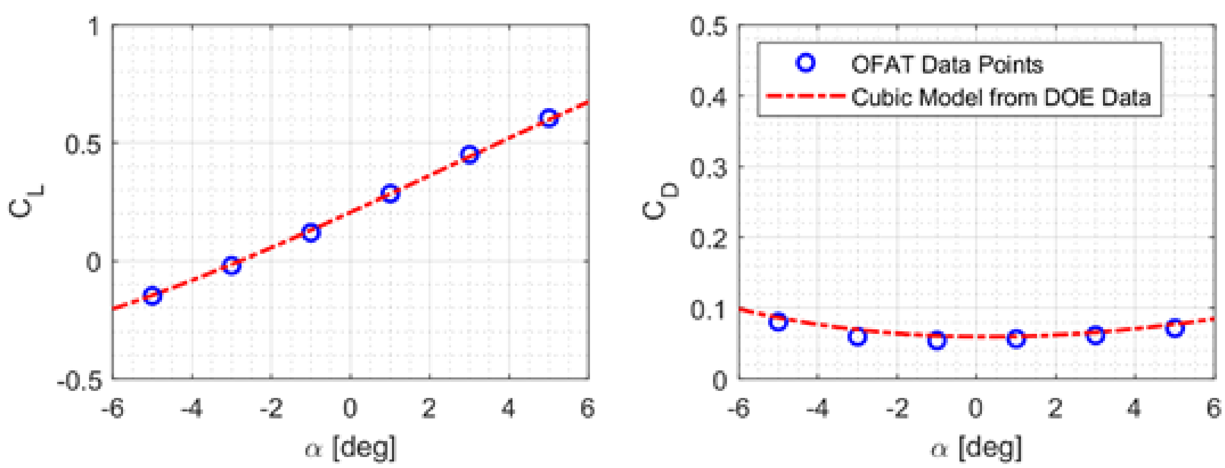


Fig. 18 Comparison of OFAT data and the aero model for the LA-8 bare airframe DOE test.

Even though the previous comparison is encouraging, the original intent was to include much more detailed and quantitative comparisons for powered OFAT and DOE testing of the LA-8 configuration. To date the COVID-19 pandemic has delayed obtaining the additional test data required.

Planned additional near-term LA-8 wind tunnel testing includes the following:

1) DOE hover testing with the LA-8 airframe mounted both vertically and horizontally in the test section to help resolve the questions regarding how the test section wall, floor, and ceiling flow interactions affect the results.
2) OFAT hover testing with the LA-8 airframe mounted both vertically and horizontally in the test section. Performing these OFAT runs while the airframe is mounted for the DOE tests will minimize the time required to get this additional comparison data.
3) Repeat runs of the higher dynamic pressure forward flight mode DOE runs from the summer of 2019 test where some of the elevons were inoperable. (Several of the original elevon servos burned out near the end of the DOE test, and the elevons had to be locked in their nominal neutral positions for some of the final DOE run blocks. All the elevon servos have since been replaced with higher capacity units that should be able to handle the higher loading.)
4) As with the hover testing, a limited set of forward flight mode OFAT test runs at the same dynamic pressures will also be made to allow detailed comparisons with the DOE run results.
5) Depending on test times and priorities, consideration will be given to possibly including bare airframe test runs along with some of the previous cases. Switching to the “bare airframe” configuration would consist of folding back the propellers and leaving the motors unpowered. (No removal or replacement of hardware will be required.)
6) Depending on test times and priorities, consideration will be given to possibly including some test runs exploring the potential benefits of keeping the fuselage angled nose down through most of the transition from hover to forward flight. (Reference the Sec. VI discussion about Fig. 10.)

Longer-term wind tunnel testing plans for the LA-8 airframe and other VTOL configurations include testing on a 3-degree-of-freedom (3-DOF) rig that will allow pitch, roll, and yaw motion. This method will provide a means to obtain dynamic derivatives and to test control approaches by “flying” the vehicle in the wind tunnel.

XI. Concluding Summary Remarks

New VTOL vehicle designs with complex aerodynamic characteristics and large numbers of independent variables present significant challenges for wind tunnel testing. Building from previous testing experience with the GL-10 aircraft, several new test techniques were formulated and tested for the LA-8 aircraft in multiple wind tunnel tests. The findings and overall conclusions from this effort are summarized as follows:

A. Stepping through dynamic pressure settings in small increments while adjusting propeller thrust and wing-tilt angles to achieve a “trimmed” condition where lift equals flight weight, net axial force is zero, and pitching moment is zero was a simple wind tunnel test technique to: 1) establish that the LA-8 airframe tested has sufficient thrust and control authority to maintain a constant trimmed attitude at any speed between hover (with wings near vertical) and forward flight mode (with wings nominally horizontal), and 2) define airframe configuration and control settings appropriate for LA-8’s transition corridor between hover and forward flight. This technique may prove useful for testing other VTOL configurations in the future.

B. Sequentially sweeping each set of control effectors (control surfaces and motors) through a range of values on either side of the “trim” setting values determined as described in Sec. V can provide an initial assessment of the vehicle’s control authority for all three axes.

C. The LA-8 airframe tested also has sufficient thrust and control authority to perform a trimmed accelerating climbout when going from hover to forward flight. The same general procedure previously used for obtaining the steady-state longitudinal trim points was followed, except lift was required to exceed the predicted flight weight, and the axial force in the forward direction was required to exceed drag. (Reference Sec. V.)

D. The LA-8 OFAT testing results from the trim and control authority assessments were used to set the independent variable ranges for the subsequent DOE testing. This ensured that the DOE testing fully covered the likely flight envelope, without spending test time evaluating test conditions that were well outside the practical flight envelope of the vehicle. (Reference Sec. VIII.)

E. Tilting the LA-8 wings changes the moment arm distances and the resulting pitching moments generated by propeller thrust and wing aerodynamic forces. At some wing-tilt angle between the hover and forward flight configurations the direction of the pitching moment increment about the CG from the wing aerodynamic forces will reverse. Pitching moment increments generated by propeller thrust acting about the CG will change magnitude, but will always be in the same direction as the wings tilt between the hover and forward flight configurations. (Reference Sec. VI.)

F. Initial LA-8 OFAT testing showed that using differential tilt between the two wings was not as effective for controlling pitch attitude as was originally expected. At hover and through a significant portion of the transition part of the flight envelope, changes in wing angle for either wing will tend to produce pitching moment increments in one direction for the propeller thrust, and in the opposite direction for the wing aerodynamic forces.

G. OFAT testing showed that keeping both the LA-8 wings at the same tilt angle and using differential thrust between the front and aft wing propellers is a much more effective way to control pitch attitude than by using differential wing tilt.

H. Isolated propeller testing done in January of 2020 1) confirmed significant differences between the performance of the COTS and custom-made propellers, 2) provided data for a key component for possible future buildup aerodynamic modeling of LA-8, and 3) informed the overall aerodynamic model development work. (See Ref. [7].)

I. Bare airframe unpowered DOE testing of LA-8 in February of 2020 provided data for possible buildup aerodynamic modeling, provided configuration-consistent comparison data with OFAT testing done in the spring of 2019, and informed the overall LA-8 aerodynamic model development work. However, bare airframe data is challenging to superimpose with isolated propeller and powered-airframe data for aerodynamic model development using a buildup approach, particularly in the transition flight regime.

J. The complicated and changing nature of the aerodynamics and stability characteristics of LA-8 as the wings tilt through transition flight present significant challenges for using the component testing and buildup approach for aerodynamic modeling. Presently the use of the powered-airframe DOE test data alone or in combination with isolated propeller data produces the best aerodynamic model [8].

K. Because of 1) the large number of independent variables, 2) multiple possible control allocation strategies for controlling the vehicle or transitioning between hover and forward flight, and 3) the lack of a historical database for complicated VTOL designs like LA-8, DOE testing is currently the only known practical way to experimentally obtain all the aerodynamic interaction data without making major simplifying assumptions that could miss critical issues affecting safety, or conversely, opportunities to operate in ways not originally anticipated.

L. Although DOE theory and the LA-8 bare airframe testing provide some basis for comparing results, the replacement of the aft wingtip motors and propellers with different performance characteristics, and the rearrangement of the other CW and CCW propellers means no major comparisons can be made between the spring 2019 OFAT testing results and the summer DOE testing results. (Additional OFAT/DOE comparison wind tunnel testing is planned for the next LA-8 entry in the 12-Foot Tunnel.)

M. Because of wind tunnel test section wall, floor, and ceiling interactions, LA-8 hover testing results may not accurately reflect flight conditions for hover in ground effect or at altitude. (Reference Sec. X.) Future planned LA-8 hover testing in 12-Foot will include mounting the airframe vertically (so the propeller flow is aligned with the normal airflow through the test section) to help resolve some of these questions.

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References

[1] Busan, R. C., Rothhaar, P. M., Croom, M. A., Murphy, P. C., Grafton, S. B., and O'Neal, A. W., "Enabling Advanced Wind-Tunnel Research Methods Using the NASA Langley 12-Foot Low Speed Tunnel," *14th AIAA Aviation Technology, Integration, and Operations Conference*, AIAA Paper 2014-3000, 2014.

[2] Murphy, P. C., and Landman, D., "Experiment Design for Complex VTOL Aircraft with Distributed Propulsion and Tilt Wing," *AIAA Atmospheric Flight Mechanics Conference*, AIAA Paper 2015-0017, 2015. https://doi.org/10.2514/6.2015-0017.

[3] Rothhaar, P. M., Murphy, P. C., Bacon, B. J., Gregory, I. M., Grauer, J. A., Busan, R. C., and Croom, M. A., "NASA Langley Distributed Propulsion VTOL Tilt-Wing Aircraft Testing, Modeling, Simulation, Control, and Flight Test Development," 14th AIAA Aviation Technology, Integration, and Operations Conference, AIAA Paper 2014-2999, 2014. https://doi.org/10.2514/6.2014-2999.

[4] North, D. D., Howland, G., and Busan, R. C., "Design and Fabrication of the LA-8 Distributed Electric Propulsion VTOL Testbed," *AIAA SciTech 2021 Forum*, 2021. To be published.

[5] McSwain, R. G., Geuther, S. C., Howland, G., Patterson, M. D., Whiteside, S. K., and North, D. D., "An Experimental Approach to a Rapid Propulsion and Aeronautics Concepts Testbed," NASA TM–2020-220437, 2020.

[6] Geuther, S. C., North, D. D., and Busan, R. C., "Investigation of a Tandem Tilt-wing VTOL Aircraft in the NASA Langley 12-Foot Low-Speed Tunnel," NASA TM–2020–5003178, 2020.

[7] Simmons, B. M., and Hatke, D. B., "Investigation of High Incidence Angle Propeller Aerodynamics for Subscale VTOL Aircraft," NASA TM, 2021. To be published.

[8] Simmons, B. M., and Murphy, P. C. "Wind Tunnel-Based Aerodynamic Model Identification for a Tilt-Wing, Distributed Electric Propulsion Aircraft," *AIAA SciTech 2021 Forum*, 2021 To be published.

[9] Simmons, B. M., "System Identification for Propellers at High Incidence Angles," *AIAA SciTech 2021 Forum*, 2021. To be published.

[10] Murphy, P. C., Simmons, B. M., Hatke, D. B., and Busan, R. C., "Rapid Aero Modeling for Urban Air Mobility Aircraft in Wind-Tunnel Tests," *AIAA SciTech 2021 Forum*, 2021. To be published.

[11] Murphy, Patrick C., Buning, Pieter G., Simmons, Benjamin M., "Rapid Aero Modeling for Urban Air Mobility Aircraft in Computational Tests," *AIAA SciTech 2021 Forum*, 2021. To be published.

[12] Murphy, Patrick C. and Landman, Drew, "Experiment Design for Complex VTOL Aircraft with Distributed Propulsion and Tilt Wing," *AIAA Atmospheric Flight Mechanics Conference*, AIAA Paper No. 2015-0017., 2015. https://doi.org/10.2514/6.2015-0017.

[13] Landman, D., Simpson, J., Mariani, R., Ortiz, F., and Britcher, C., "Hybrid Design for Aircraft Wind-Tunnel Testing Using Response Surface Methodologies," *Journal of Aircraft*, Vol. 44, No. 4, 2007, pp. 1214–1221. https://doi.org/10.2514/1.25914.

[14] Foster, J. V., and Hartman, D., "High-Fidelity Multi-Rotor Unmanned Aircraft System (UAS) Simulation Development for Trajectory Prediction Under Off-Nominal Flight Dynamics," *17th AIAA Aviation Technology, Integration, and Operations Conference*, AIAA Paper 2017-3271, 2017. https://doi.org/10.2514/6.2017-3271.

[15] Owens, D. Bruce, Brandon, Jay M., Croom, Mark A., Fremaux, C. Michael, Heim, Eugene H., and Vicroy, Dan D. "Overview of Dynamic Test Techniques for Flight Dynamics Research at NASA LaRC (Invited)," *25th AIAA Aerodynamic Measurement Technology & Ground Testing Conference*, AIAA Paper 2006-3146, 2006. https://doi.org/10.2514/6.2006-3146.

[16] Montgomery, D. C., Design And Analysis of Experiments, 8th ed., John Wiley & Sons, Inc., Hoboken, NJ, 2013.