

# LEAPTech/HEIST Experiment Test and Evaluation Summary

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The Leading Edge Asynchronous Propeller Technology (LEAPTech) project tested the Hybrid-Electric Integrated Systems Testbed (HEIST) and was intended for a general aviation sized aircraft with Distributed Electric Propulsion (DEP) to show large improvements with regards to efficiency, emissions, safety and operating costs. The wing was designed for high loading to improve ride quality and show improved takeoff and landing characteristics. The full-scale test article wing had a 31-foot-span, had integrated electric motors, was mounted on a truck 20 ft. above ground and driven in a simulated flight test environment at various velocities up to 70 miles per hour. The simulated flight test varied primarily angle of attack and flap settings. These tests were conducted to obtain data and verify blown wing performance primarily with regards to lift. The experimental test results are presented.

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## Nomenclature

$\alpha$	=	Angle of attack in degrees
AoA	=	Angle of attack
AFRC	=	Armstrong Flight Research Center
ARMD	=	Aeronautics Research Mission Directorate
CFD	=	Computational Fluid Dynamics
$C_D$	=	Aircraft coefficient of drag force
$C_L$	=	Aircraft coefficient of lift force
EAFB	=	Edwards Air Force Base

## 1. Introduction

The Leading Edge Asynchronous Propeller Technology (LEAPTech) project tested the Hybrid-Electric Integrated Systems Testbed (HEIST). The HEIST experiment was a full-sized wing was mounted on a truck 20 ft. above ground, see figure 1. HEIST was sized for general aviation aircraft with Distributed Electric Propulsion (DEP) to show large improvements with regards to efficiency, emissions, safety and operating costs. The experiment was designed to improve efficiency, and to show high wing loading to improve ride quality and show improved takeoff and landing characteristics. The test article wing was full scale, had a 31-foot-span, had integrated electric motors, and driven in a simulated flight test environment at various velocities up to 70 miles per hour. The simulated flight test varied primarily angle of attack and flap settings. These tests were conducted to obtain data and verify blown wing performance primarily with regards to lift. The experimental test results are presented.

The HEIST experiment was a joint effort between the National Aeronautics and Space Administration (NASA) Armstrong and Ames centers and Joby Inc.<sup>1</sup> The experiment was devised as a low-cost alternative to wind tunnel testing. The project had challenges due to inclement weather in the heart of testing, finicky equipment and test conditions that were not as steady as previously thought. The primary objective of the experiment was to provide confirmation that the blown wing could reach lift coefficients of 4.0 or higher. Several sources of error contributed to reduced confidence in the data presented. The test data presented within is not intended and does not have sufficient quality to be used for close comparison to analytical or computational methods.

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## 2. Test Article Description

The wing on the HEIST experimental setup was designed to both streamline construction and to deliver useful data/analysis. Detailed specification is presented by Stoll<sup>1</sup>. The center section is a straight wing section and the primary wing sections were designed with constant linear taper, sweep, and twist. Each of the eighteen-brushless electric Joby JM1 motors were evenly spaced span wise and are mounted in nacelles along the wing leading edge<sup>1</sup>, see Figure 1. Fowler flaps along the entire span between the wingtip nacelles and the root unswept section were configured to manually be set at 0, 10 ,20 ,30 or 40 degrees. Wing angle of attack adjustment were also made manually by adjusting the pin position on each of the supporting structure connections/load cell assembly with the wing, a detailed picture is presented by Stoll<sup>1</sup>. A blown configuration, defined as with propellers, no spinners, and motor on as well as an unblown figuration, defined as without propellers, no spinners, and motor off were tested.



**Figure 1. LEAPTech Test Article**

The steel wing support structure was suspended on the truck frame with airbags, to isolate the support structure from road vibrations. Large water tanks are mounted to this structure below the airbags to lower the center of mass of this suspended structure. Sway braces were installed to constrain airbag lateral displacement. The wing was mounted to the support structure pictured in figures 1 and 2.



**Figure 2. Unblown configuration HEIST Test Article with Propellers Removed**

## 3. Instrumentation

The HEIST experiment instrumentation suite included, GPS, air data probe, accelerometers, a custom force balance with 7 load cells, pressure transducers, strip-a-tubing steady pressure sensor strips, weather stations and motor controller communication. The onboard GPS measured ground speed. The air data probe measured airspeed, static pressure, and sideslip angle. Accelerometers included three uniaxial, three biaxial, and two triaxial to measure structural dynamics. There was a custom balance with load cells, four to measure lift/pitch /roll, two to measure drag/yaw and one to measure lateral forces. All of the load cells were used to resolve vertical force, axial force, side force, and pitching moment. There were eight high-speed transient pressure transducers and five chord wise strip-a-tubing steady pressure sensor strips with a total of 120 pressure measurements. Weather station anemometers were

located at each end of the 12000-foot runway. The motor controller communication provided RPM of each motor and input power into each motor.

#### 4. Test Summary

All full-scale testing was conducted on the HEIST configuration wing that was in the blown and unblown configuration with fowler flap setting at 40 degrees, see Tables 1 and 2.

**Table 1. Unblown (No Propeller, No Spinner, Motor Off) Test Matrix**

Flap Angle 40 Degrees	Wing Angle (Degrees)								
	0	3	6	9	12	13.5	14/15	17	19
Complete	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No

**Table 2. Blown (With Propeller, No Spinner, Motor On) Test Matrix**

Flap Angle 40 Degrees	Wing Angle (Degrees)								
	0	3	6	9	12	13.5	14/15	17	19
Complete	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

#### 5. Test Uncertainty

Large experimental uncertainties were identified toward the end of testing and after testing was complete. The experiment configuration yielded a nonlinear environment with significant contaminatory data components. Although the test did have a GPS it was difficult to hold each test point condition accurately because the truck did not have a working speedometer. Each test condition was regulated by the truck RPM which resulted in 3-5 MPH variability. Additionally, there was an unexplained propulsion system asymmetry. During data analysis motors on left wing were identified as absorbing about 15% more power than the motors on right wing, while indicating the same RPM. This led to a thrust imbalance of at least 40 lbf. These sources of error contributed to the reduced confidence in the data presented in the Results & Analysis section below. Unidentified and unquantified sources of error still exist within the data. Only the test data is presented in this paper where ellipses were used to identify the known error.

An attempt was made to use CFD to understand some of these sources of error but there was significant variability between multiple CFD results and test condition results. Additionally, the bulk of available CFD results did not include the truck, truss work, or potential ground effects. As a consequence, the CFD and test data did not converge to a solution with error bounds that sufficiently verify either sets of data.

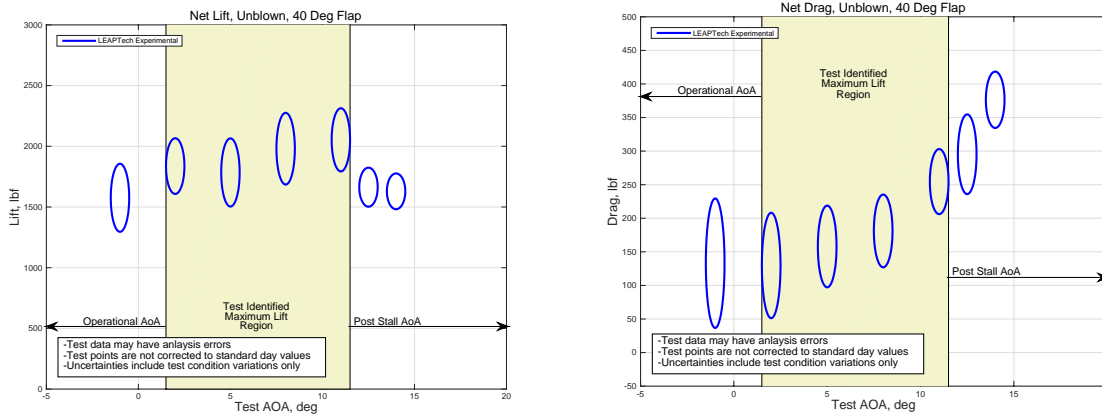
#### 6. Results & Analysis

A summary of the lift and drag forces and coefficients for both the blown and unblown configuration are presented. The unblown figuration, defined as without propellers, no spinners, and motor off. The blown configuration is defined as with propellers, no spinners, and motor on data are presented below. Although the data does not provide a clear angle of attack where a maximum lift occurs or where the wing stalls the overall data in the range of maximum lift does indicate a substantial increase in lift and lift coefficient for the blown configuration.

##### Unblown Test Results

The unblown configuration test results are presented below in figures 3 and 4. Uncertainties in the data include test condition variations only, other unidentified uncertainties could exist. The blue ellipses show 2D experimental uncertainty bounds. The data were not corrected to standard day values. It is possible that the test data that is presented could have analysis errors.

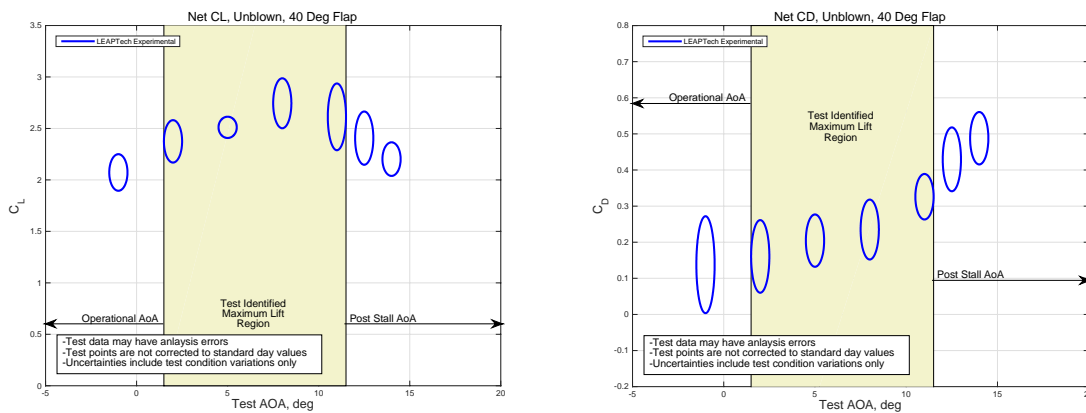
Figure 3 shows the net lift and drag for the unblown experimental configuration results. The net lift plot shows a wide range of angles of attack between 1.5 and 11.5 degrees where the maximum lift could exist. In this range, the maximum lift is indicated between 1500 lbf. at 5 degrees AoA and 2300 lbf at 11 degrees AoA. The net drag plot for the unblown configuration in has a general drag bucket shape and the maximum lift bounds are translated to this plot. Potential operational AoA and post stall areas are identified to the left and right of the maximum lift area in each plot.



**Figure 3. Unblown Wing (Props Removed) - Net Lift and Drag**

**Note:** “Test AOA” is angle between ground and wing-mounting lugs parallel to the chord line at the plane of symmetry.

Figure 4 shows the lift and drag coefficients for the unblown experimental configuration results. The lift coefficient plot again shows a wide range of angles of attack between 1.5 and 11.5 degrees where the maximum lift coefficient could exist. In this range, the maximum lift coefficient is indicated between a low of 2.2 at 3 degrees AoA and a high of 3.0 at 9 degrees AoA. The drag coefficient plot for the unblown configuration again has a general drag bucket shape and the maximum lift bounds are translated to this plot. Potential operational AoA and post stall areas are identified to the left and right of the maximum lift coefficient area in each plot.



**Figure 4. Unblown Wing (Props Removed) - Lift and Drag Coefficients**

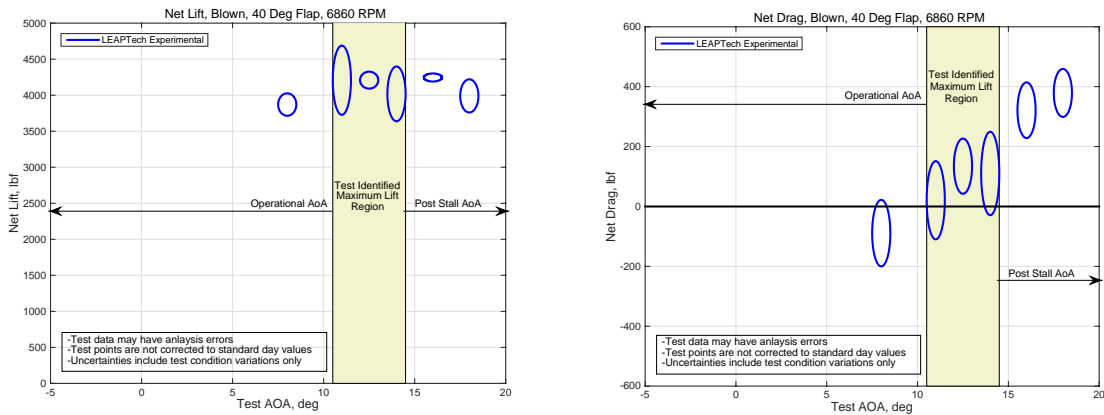
**Note:** “Test AOA” is angle between ground and wing-mounting lugs parallel to the chord line at the plane of symmetry.

### Blown Test Results

The blown configuration test results are presented below in figures 5 and 6. Uncertainties in the data include test condition variations only, other unidentified uncertainties could exist. Again, the blue ellipses show 2D experimental uncertainty bounds. The data were not corrected to standard day values. It is possible that the test data that is presented could have analysis errors. Figure 5 shows the net lift and drag for the blown experimental configuration.

Figure 5 shows the net lift and drag for the blown experimental configuration results. The net lift plot shows a range of angles of attack between 10.5 and 14.5 degrees where the maximum lift could exist. In this range, the maximum lift is indicated between 3600 lbf at 14 degrees AoA and 4700 lbf at 11 degrees AoA. The net drag plot for the blown configuration in has an overall linear shape and the maximum lift bounds are translated to this plot.

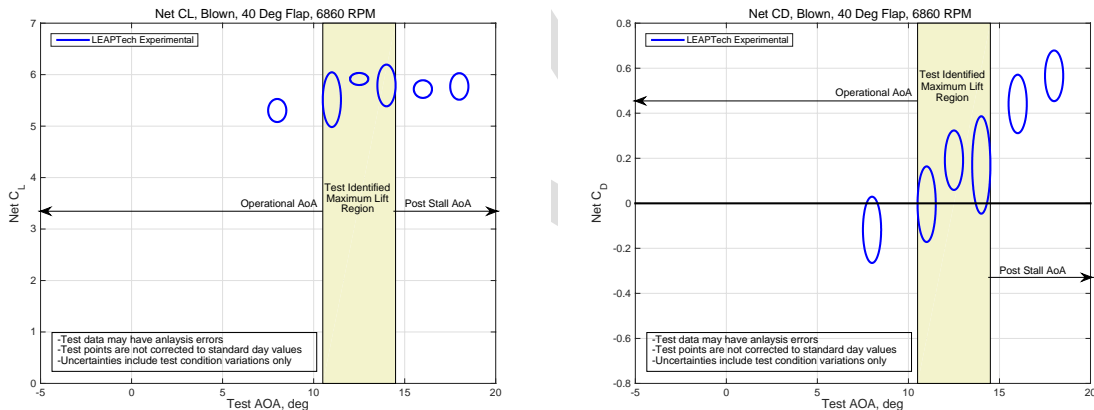
Potential operational AoA and post stall areas are identified to the left and right of the maximum lift area in each plot.



**Figure 5. Blown Wing (Props Powered) - Net Lift and Drag**

*Note:* “Test AOA” is angle between ground and wing-mounting lugs parallel to the chord line at the plane of symmetry.

Figure 6 shows the net lift and drag for the blown experimental configuration results. The lift coefficient plot again shows a range of angles of attack between 10.5 and 14.5 degrees where the maximum lift could exist. In this range, the maximum lift is indicated between 6.3 at 14 degrees AoA and 5.0 at 11 degrees AoA. The drag coefficient plot for the blown configuration again has a general linear shape and the maximum lift bounds are translated to this plot. Potential operational AoA and post stall areas are identified to the left and right of the maximum lift area in each plot.



**Figure 6. Blown Wing (Props Powered) - Lift and Drag Coefficients**

*Note:* “Test AOA” is angle between ground and wing-mounting lugs parallel to the chord line at the plane of symmetry.

## Test Results Summary

The net lift and lift coefficient plots for the unblown and blown configuration are irregular due to the known test uncertainty. The lift coefficient results indicate  $C_L$  values of 2.2 to 3.0 with a flap setting of 40 degrees for the unblown configuration and  $C_L$  values of 5.0 to 6.3 for the same flap setting on the blown configuration. The net drag and drag coefficient plots for the unblown and blown configuration are more regular but significant uncertainty remains.

## 7. Conclusion

The paper presented results of the Leading Edge Asynchronous Propeller Technology (LEAPTech) project tested the Hybrid-Electric Integrated Systems Testbed (HEIST) experiment. The experiment was designed to improve efficiency for general aviation aircraft configurations, to show high wing loading to improve ride quality and show improved takeoff and landing characteristics.

The HEIST experiment data was not sufficient to be used as a one-to-one verification set primarily due to an inability to accurately measure the test condition. The experimental results were compromised by numerous error sources. Some of these error sources included velocity variability, an unexplained propulsion system asymmetry, and unidentified sources of error that exist within the data. Some examples of error that could not be quantified were: flow interference of truck, truss work, and ground effects; an uncalibrated and nonlinear force balance; and possible aliasing of the data.

The HEIST experiment data was shown to indicate lift coefficient  $C_L$  values of 2.2 to 3.0 with a flap setting of 40 degrees for the unblown configuration. The experimental data was also shown to indicate  $C_L$  values of 5.0 to 6.3 for the same flap setting on the blown configuration. No comparison was made to CFD or analytical methods because large variability existed in all of the sets of data.

Although no close comparison to CFD is made, the experiment was based on CFD results that showed high coefficient of lift values are possible using the leading edge asynchronous propeller technology. Based on the limited findings in this experiment, this study indicates high coefficient of lift values are possible using the leading edge asynchronous propeller technology.

## 8. Acknowledgments

The author would like to thank Sean Clarke and Starr Ginn, who oversaw the experimental and execution aspects of the program, acted as liaisons with NASA, provided additional resources. This research was funded by NASA Langley Research Center in support of its efforts to pursue understanding of the opportunities provided through highly coupled multi-disciplinary integration of distributed electric propulsion. This research involved a close collaboration across NASA Langley, Armstrong, Ames, and Joby Aviation with participation from a broad group of researchers. The author would like to extend appreciation to Karen Deere and Sally Viken, who provided the FUN3D analysis.

## References

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

<sup>2</sup> Murry, J., Lechniak, J. A., "The LEAPTech Experiment, Approach, Results, Recommendations", Oct 20, 2016, DFRC-E-DAA-TN36158.