The IDEAL Project: An Interim Report

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Introduction to the JabirWatt experiments

IDEAL (Integrated Distributed Electric-Augmented Lift) makes use of multiple Electric Ducted Fans (EDFs) mounted on a lifting surface, so they not only propel the aircraft but the high-velocity air over the top surface of the wing alters its aerodynamic properties. This self-funded, four-year project has made extensive use of wind tunnel testing with confirming in-flight testing using the JabirWatt aircraft. In-flight Jabirwatt testing began in September 2019. This short paper gives a brief overview of the project and the promising results to date.

Figure 1: The JabirWatt

The JabirWatt[1] is a stock Jabiru J230-D complete with its original Jabiru 3300 IC engine and with four EDFs mounted inboard on the wings. These EDFs are 120mm off-the-shelf model airplane units powered by a custom LiPoFe 120wh/kg battery pack[2]. The four EDFs are not enough to sustain flight, but sufficient to collect data to compare with wind-tunnel and theoretical results.

The goal of this project is to understand the potential for using distributed EDFs to create eSTOL aircraft leveraging the potential of electric Propulsion Airframe Interaction (PAI). Electric PAI with many small electric propulsors allows the propulsion to be distributed, affecting the airflow over the wing in ways not possible in the past. PAI is not new concept. It has its roots in the 1940s with Willard Custer's Channel Wing, evolving in the 1960s and 70s with the jet turbine-powered Boeing YC-14 and NASA's QSRA. Electric power allows distributed propulsion in ways not possible with Custer's IC engines or the research jet turbines. The hypothesis here is that electric PAI has good potential for eSTOL aircraft development and may provide benefits aircraft cruise.

[1] View a video of the Jabirwatt in flight: www.davidullman.com/the-Jabirwatt
[2] 16, CALB CAM72Fi 3.2V 72 Amp Hour cells.

Summary of Results and Caveats

Results of Jabirwatt testing September through November 2019 has shown:

1. Significant decrease in the stall speed.
2. Significant increase in all features of the lift curve, the zero intercept (Cl_0) the lift curve slope (Cl_α), and the maximum lift coefficient (Cl_{max}).
3. Significant decrease in takeoff distance potential
4. Improved cruise potential
5. Minimal additional drag when EDFs are unpowered
6. Good agreement between the wind tunnel and in-flight results

Before detailing these results, some caveats:

- This is an interim report. Both wind tunnel and in-flight experiments are on-going, with results continuously updated. What is presented here are firm results that have repeatedly been verified.
- All EDFs and controllers are high-end off-the-shelf model airplane components with no effort to optimize them. EDFs for wind tunnel testing are 50mm and those on the JabirWatt 120mm.
- While the EDF-on-a-pylon configuration shown in Figure 1 has been optimized through L18 wind tunnel experiments, work on in-wing and other configurations are on-going. The EDF-on-a-pylon configuration was developed first as it is the simplest and most flexible for experimentation.
- All JabirWatt data is based on four EDF with 13kw (17.5 hp) of maximum power, a fraction of that needed to sustain the airplane.
- Flap data was taken using the stock Jabiru flap system. An aerospace engineering master's project has begun a project to optimize the flap configuration.

Results

Each of the six results are supported here. Other information is available on the project's web site: www.davidullman.com/aeronautics.

1. Inflight Data Shows a Decrease in Stall Speed

Although the JabirWatt has only 4 EDFs mounted and was limited to 13kw max, there was a consistent decrease in stall speed with the EDFs on. As shown in Table 1. (based on repeated test points), the stall speed was reduced 2-3 kts.

	Stall speed IAS (kts)		
Flaps	EDFs off	EDFs on	Delta IAS
up	41	39	2
half	37	34	3
full down	36	33	3

Table 1: JabirWatt Stall Speed

2. IDEAL Dramatically Increases the Lift Coefficient

Further, the data taken during these flight tests also show a change of CL_{max}, the maximum lift coefficient as shown in Table 2. Here, the value of 1.7 for the plain wing agrees well with the published value of 1.5 for the NACA 4415 airfoil[3] which is very similar to the 4414 airfoil on the JabirWatt. With the four EDFs turned on, the Cl increases to 1.85, a 9% increase. The maximum lift for the plain wing 4415 is at an angle of attack of 15 degrees (see Figure 2). With the four EDFs on, the angle of attack at stall increases to 18.6 degrees, a 24% increase.

With the flaps deployed, the effect on Clmax is even more dramatic, increasing to 16%. These results are gained with only four EDFs affecting only 13% of the total wing area.

	CL max		
Flaps	EDFs off	EDFs on	% increase
up	1.70	1.85	9%
half	2.03	2.35	16%
full down	2.13	2.47	16%

Table 2: Clmax Results

These results can be extrapolated for the case when the effects of the EDFs cover the entire wing area. The increase in CL_{max} was from 1.7 to 1.85 with the EDFs only affecting 13% of the total wing area. This implies that the Cl for the EDF affected area at stall is 2.89, while the remaining 87% is at 1.7. Similarly, with the flaps down, the Cl_{max} for the portion of the wing affected by the EDFs is 7.56.

Wind tunnel[4] test results for a NACA 4414 airfoil show the overall effects on the lift coefficient. The lower curve in Figure 2, shows the text-book lift curve slope for a NACA 4414 airfoil with experimental points from 2-D wind tunnel tests superimposed. Note that JabirWatt results gave Clmax = 1.7, acceptably close to the data here. The upper curve is fit to data for the same wing with EDFs providing flow over the entire test specimen. Here Cl_0 (the lift coefficient at zero angle of attack) is increased by 135%, the lift curve slope from 0 to 5 degrees is increased by 43%, and the angle of attack for Clmax increased from 15 deg to more than 20deg (the limit of the test fixture).

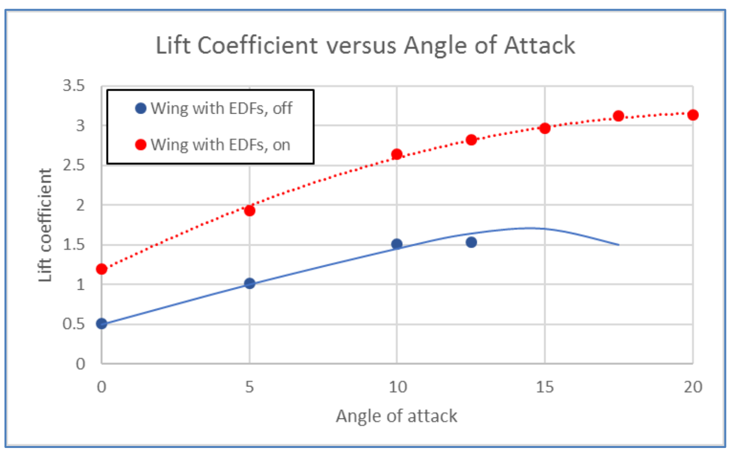

Figure 2: Lift curve

[3] http://airfoiltools.com/airfoil/details?airfoil=naca4412-il
[4] For details on the wind tunnel see https://www.davidullman.com/wind-tunnel-facility

3. IDEAL Has the Potential to Significantly Decrease Takeoff Distance

The stall numbers from the previous sections imply that with a full complement of EDFs the Jabirwatt could take off with a ground roll of 315ft (96m) clean or 120ft (36m) with flaps deployed. A stock Jabiru J230-D has a ground roll of 817 ft (249m), clean. With improved EDFs and other design improvements, these distances can be further reduced.

4. IDEAL also Offers a significant Cruise Potential

The increase in lift coefficient seen in Figure 2, at even low angles of attack, offers some significant design options. If the lift coefficient is doubled (Figure 2 shows 135% improvement at zero angle of attack), then the wing area can be decreased by a similar proportion, greatly reducing parasite drag. Optionally, the cruise velocity can be increased, or some mix of the two options.

5. The Drag Increase Due to the EDFs Is Minimal.

While the frontal area of the EDFs on the JabirWatt in Figure 1 appears to be large and thus be draggy, this is not the case as much of the air that appears to be blocked passes through the EDF blades. In-flight measurements show that at cruise speed with the fans wind milling, each unit adds 1.5 lb. (.7kg) of drag. The mounting of the EDFs could be refined, or the blades locked from rotation or feathered further reducing this value.

6. There is a simple theory that can be used to explain and model the IDEAL effect.

The IDEAL concept can be explained in terms of classic airfoil circulation theory that replaces a lifting surface with a rotating vortex so the air on the top surface is moving faster than that on the bottom surface. With some simplifying assumptions the lift coefficient can be calculated by:

$$Cl = C1 + C2\ Ve/Vb$$

where Ve is the mean velocity of the air over the top surface of the wing, Vb is the velocity along the bottom surface, and C1 and C2 constants. IDEAL uses the exhaust of the EDFs to not only propel the airplane, but also uses the exhaust air to increase Ve and thus the lift coefficient. While this equation seems overly simplistic, it has shown to be a good model for both the wind tunnel results and those on the JabirWatt. Further this form, with modification, can be used to model the effect of angle of attack and flap angle. These relationships have been confirmed with both wind tunnel and flight data.

What this model tells us is that, the higher the top surface velocity is over a portion of the airfoil, the higher the lift coefficient on that section of the wing. The goal then is to design the EDFs to not only provide thrust, but to increase the air velocity as high as possible over as much of the wing surface as possible.

7. Good Agreement Between Wind Tunnel and In-Flight Data

In-flight testing compares well with wind tunnel results and shows the potential for IDEAL. Figure 3 is a compilation plot of the 2-D wind tunnel lift coefficient results from Figure 2, results from JabirWatt testing and projections using the model described in the previous section. The information on the plot is explained below beginning with the wind tunnel data.

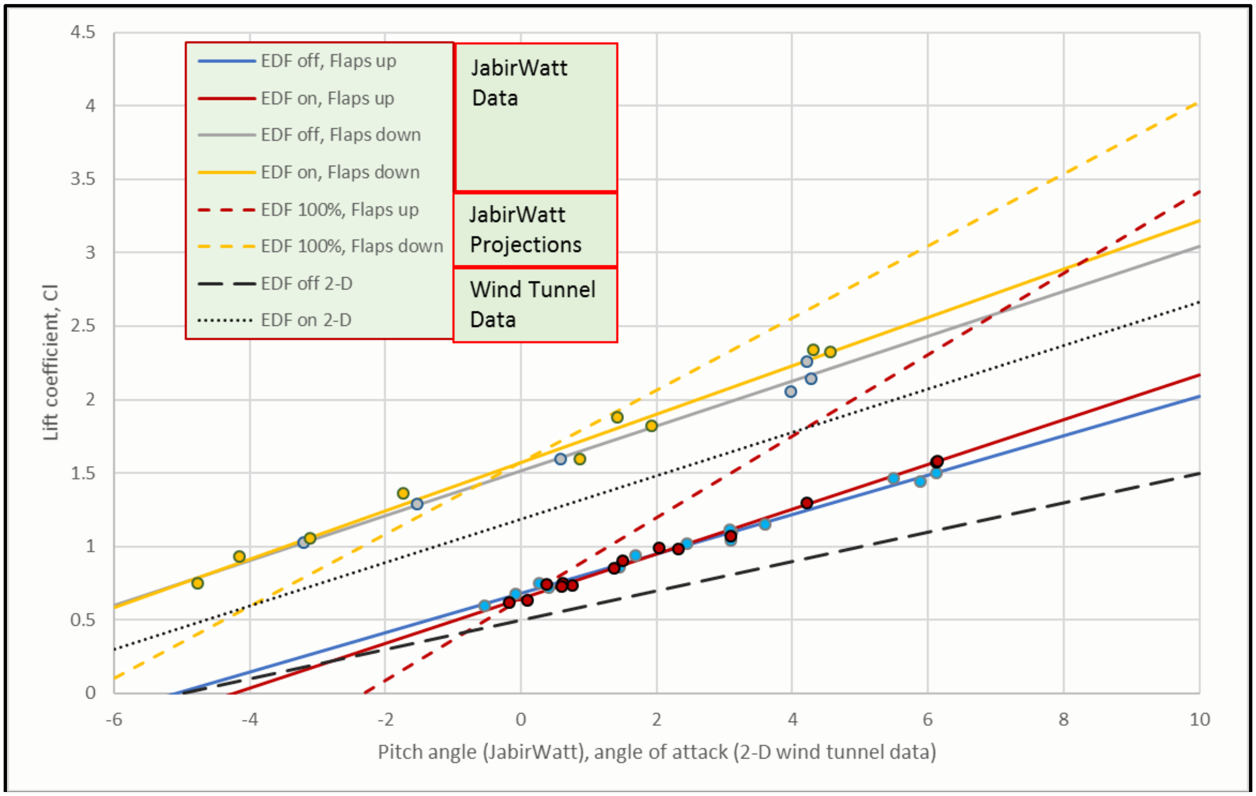

Figure 3: Lift Coefficient Comparisons

The two wind tunnel results from the Figure 2 for 2-D wind tunnel results with EDFs off and with them on are reproduced here as fit by the Section 6 linear equation and shown as the two black dashed lines. This 2-D data lift data is plotted versus the angle of attack.

Data taken on the JabirWatt with four EDFs mounted but not running, and flaps up, is represented by the blue dots and fit with the blue line consistent with the Section 6 linear equation. Data with the EDFs running are similarly plotted with the red circles and line. While the difference seems small, it is statistically significant and gained with only four model airplane EDFs. All JabirWatt data on this plot is versus pitch angle as this is measured while the angle of attack is not.

Data with the JabirWatt's flaps down at 30deg are similarly shown as the grey and yellow dots and lines. These are also statistically significantly different.

The dashed red and yellow lines are projections with EDFs providing Propulsion Airframe Interaction (PAI) to the entire wing surface. The yellow curve, for the flaps down, shows Cl =4 at 10 degrees. As discussed in Section 2, the lift coefficient continues to a Cl_{max}= 7.56 at 18.6 degrees.

8. IDEAL Potential

Modeling[5] using the Breguet Range Equation modified for electric airplanes shows that eSTOL has strong potential benefits for electric airplanes. In his 2018 keynote address[6] at the Sustainable Aviation Symposium "*Electric Air Vehicle Performance Prospects: Comparing eVTOL versus USTOL*" the first author found the following (Note that "USTOL" implies ultra-performance eSTOL as is true with IDEAL):

- eSTOL can be designed to give very short take-off distances
- VTOLs need 2-5 times the power of eSTOL to take-off
- eSTOL has nearly twice the range of eVTOL regardless of battery maturity.

Based on the findings to date tempered by the caveats at the beginning of this paper, IDEAL is certainly a concept worth further development. The next section itemizes the near-term plan for further research.

9. Next Steps

Near term efforts for the IDEAL Project are:

1. Flap optimization
   All flap data in the tunnel and on the JabirWatt has used the stock Jabiru wing-flap combination. A project was begun in July 2019 to study the flap design. A master's degree student from Oregon State University is preparing for wind tunnel tests in early 2020.
2. In-wing configuration design
   Early IDEA concepts had the EDFs integral with the wing. This type of configuration is being refined.
3. Airfoil shape development
   The shape of the airfoil must certainly affect the IDEAL capability. To date all work has used a NACA 4414 because that is close to what is on the Jabiru. Research here is just beginning and is not independent of the in-wing configuration.

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[5] *Comparing Electric Sky Taxi Visions*, June 2017, Dr. David G. Ullman, Vincent Homer and Patrick Horgan (CubCrafters) with consulting contributor, Richard Ouellette (Boeing Commercial). https://www.davidullman.com/air-taxi-visions

[6] https://www.youtube.com/watch?v=OiNNL87qQqQ

4. Add more EDFs to the Jabirwatt
   The existing JabirWatt batteries are current limited to 320amps (50 volts at 16kw) and can thus only power the four existing EDFs. To add four more EDFs, doubling the present number, then the batteries also need duplication. The JabirWatt weight and balance can handle up to two more battery boxes. With two additional boxes (12 EDFs) and eight more EDFs the JabirWatt could take off and cruise with marginal performance.

To make these next steps possible will also require partnership development. To date, this project has been self-funded, but its success has outgrown this source.

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