

The IDEAL for Near-VTOL Aircraft

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Executive Summary

Propellers expend power partly to provide thrust and partly to increase the velocity of the air going through it. The energy put into increasing the air velocity is wasted.

This “wasted energy” can be put to work by using many small distributed Electric Ducted Fans (EDFs) blowing over a major portion of the upper surface of the wing. The speed of the air over the top surface determines 80% of the lift generated by a wing. Spreading the high velocity air from EDFs propulsors over this surface gives dramatic benefits.

The exit flow over the upper surface increases lift and lowers induced drag. These two effects allow very short, near-VTOL take-offs, and increased cruise velocity and range. Additionally, this concept allows “sculpting” the lift distribution over the span of the wing resulting in improved reliability, control and ride qualities.

This synergy between the propulsion and aerodynamics is called Integrated Distributed Electric-Augmented Lift or IDEAL. IDEAL makes use of Distributed Electric Propulsion (DEP) to enhance the lift characteristic of a STOL aircraft.

Background

Electric airplanes will play a major role the future of aviation. Not yet clear is the forms these aircraft will take and how new infrastructures will evolve to support them. This is true of both large commercial aircraft, smaller business and personal aircraft, and air taxis. This paper is focused on design of small electric airplanes carrying one or two people, but also can be applied to larger aircraft.

The dream for small personal aircraft is one of providing near-door-to-door air transportation, one in which anybody, without need for a pilot or an airport with a long runway, can travel by air from one convenient point to another. Aircraft fulfilling this dream are being referred to as Personal Air Vehicles (PAVs) or Air Taxis (ATs). In the past these have been the vision of Sci-fi authors or wild-haired inventors covered in Popular Mechanics.

Recently, the reality has begun to evolve: Dubai has contracted with Ehang (a Chinese manufacturer of multi-copters) to provide small, one-person multi-copter air taxis in Abu Dhabi; NASA is building the X-57 Maxwell as an experimental aircraft with sixteen electric motors for testing in 2018; Airbus has just completed testing its E-Fan with two electric ducted fans; and many are developing electric aircraft that takeoff vertically and

transition to traditional flight (VTOLs). Additionally, progressive businesses are taking interest: Uber has hired the X57's project leader from NASA to develop its electric air taxi and has sponsored a symposium on the topic; Martine Rothblatt, CEO of United Therapeutics, is funding the first test flights of an electric helicopter, and Elon Musk has repeatedly indicated his interest in electric flight.

Besides being powered electrically, all of these projects focus on aircraft that can take off vertically or in a short distance, a feature needed to meet the PAV/AT vision.

There are two main technological issues that need to be resolved for successful realization of the dream: 1) battery energy density needs to greatly improve; and 2) electric aircraft design needs to be optimized to make the best use of whatever energy is available. Batteries continue to evolve with an increase in energy density of 7-8% per year and many are working on hybrid power sources. This paper focuses on the second issue: what is the best aerodynamic concept to make the most efficient use of the energy.

To date, PAV/AT concepts fall into two main categories; VTOL and STOL. Multi-copters, helicopters and other VTOLs are known to be very energy and power inefficient and thus exacerbate the battery energy density problem. While multi-copters are quite simple they are by far the most inefficient and potentially the least safe during system or partial-system failure. VTOLs that transition from vertical to horizontal flight by rotating wings or pods suffer from complexity both in their structure and their control. Thus, this paper focuses the design of non-complex aircraft to make optimal use of what energy is available and use it to greatly reduce the need for long runways and additionally, provide improved ride and control qualities. This IDEAL technology uses ducted fans to produce both thrust and lift resulting in near-VTOL takeoffs and landings, and enhanced cruise efficiency.

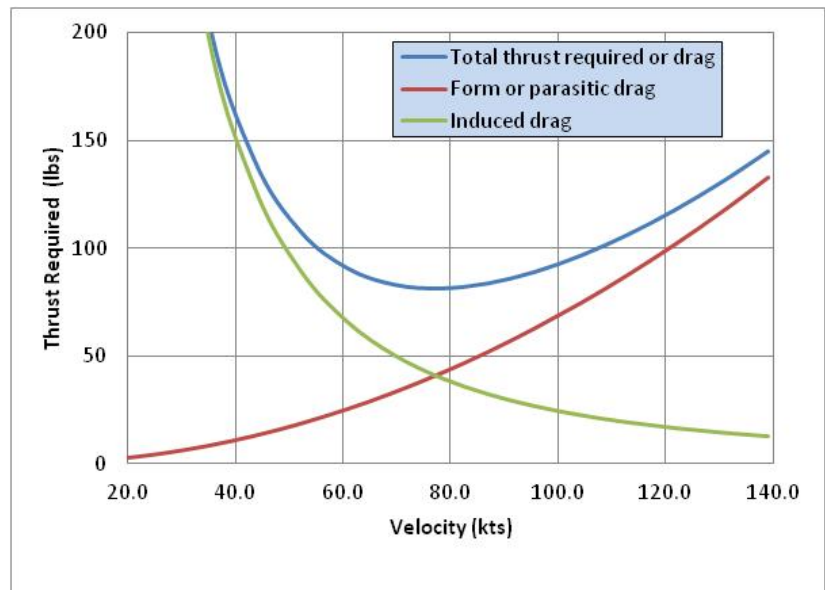
One feature of NASA's X-57 and some of the other proposed aircraft is that they are based on the premise that the most efficient use of electrical energy is to distribute it across many small propulsors that interact in some favorable way with aerodynamics. The X-57 accomplishes this with many small electric motors and propellers along the leading edge of the wing. As will be shown here, there are potentially large benefits in leveraging the synergistic interaction of propulsion with aerodynamics but the exact form of this synergy is not currently known. It is clear to the authors that there is benefit to be gained by configurations other than that used for the X-57. This paper explores a potentially better option using Integrated Distributed Electric-Augmented Lift or IDEAL.

How IDEAL works

The energy put into increasing the air velocity is wasted in traditional aircraft design. By using many small propulsors blowing over a major portion of the upper surface of the wing this "wasted energy" can be put to work. The faster moving air over the wing's upper surface increases the lift and greatly reduces induced drag. This Upper-Surface-

Blowing (USB) significantly lowers the distance needed for takeoff and increases the cruise velocity.

To understand this, first consider the figure on the right showing the thrust needed for a typical 1320 lb LSA (Light Sport Aircraft) versus its velocity. The blue curve, representing the total thrust needed, is made up of two parts. At the low end, the thrust needed is to overcome induced drag, the drag due to lift (green curve). The high end is dominated by the thrust needed to overcome parasite or form drag, the drag of the



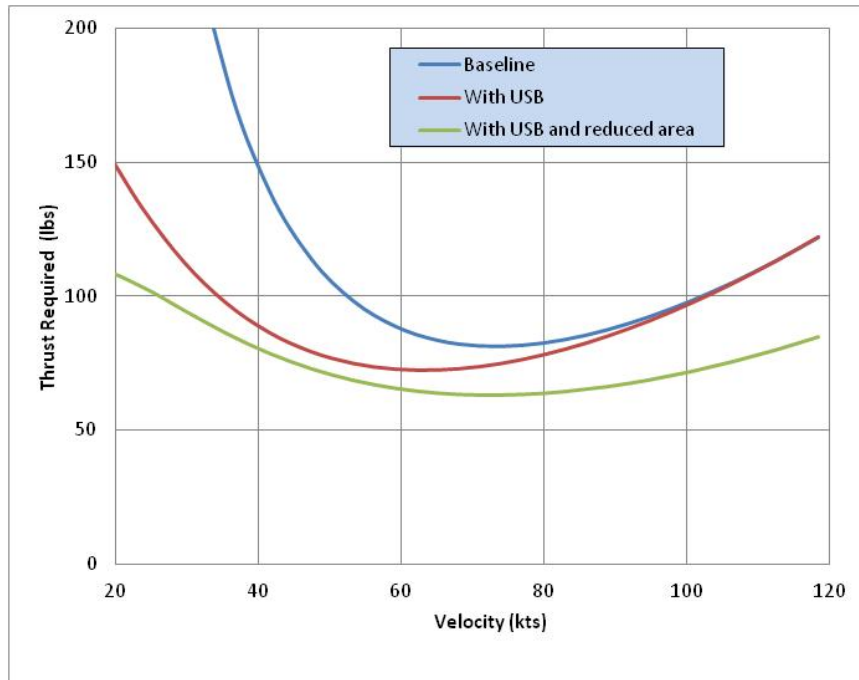
airplane pushing air out of its way (red curve). The sum of the two drag curves give the total drag, or the thrust required curve. The lowest point on this curve is the point of best performance where half the drag is due to each of the two drag components.

Traditionally, the only way to reduce the total drag was to make the wings longer and thinner reducing the induced drag; or make the airplane more streamlined, improving the form drag. However, with IDEAL, there is another option. If the distributed electric propulsion can be configured to blow air over the top surface of the wing, the air velocity seen by the top surface can be substantially higher than the actual velocity of the airplane¹. Consider that for any airfoil; about 80% of the lift is generated by the increased airstream velocity over the top surface of the wing with the remaining contributed by the bottom surface pushing the air down. The faster this airstream over the top, the more lift is generated per unit area. In fact, the lift goes up as a function of the velocity increase squared. Thus, the wasted increase in airstream velocity from the propulsors can be well utilized to increase the lift on the wing.

Even more important, the induced drag is greatly reduced. In fact, the induced drag is reduced in proportion to the ratio of the top surface airstream velocity to the free stream velocity to the fourth power. This dramatic effect has been demonstrated both analytically and experimentally.

¹ In the words of Willard Custer, the inventor of the Custer Channel Wing: "It is the speed of the air, not the airspeed."

To see how this effect can drastically change the thrust required for flight, consider the plot above. Here, as before, the blue line is the stock aircraft showing high drag (i.e. high needed thrust) at take-off and cruise velocities. By adding a minimal upper surface blowing (the red line), the needed thrust at low speed is dramatically reduced due to the reduction in induced drag. To gain



reduction at higher velocities the area of the wing can be reduced and combined with upper surface blowing so the green line can be achieved. This clearly shows less power needed at all velocities and flight at very low, near VTOL velocities.

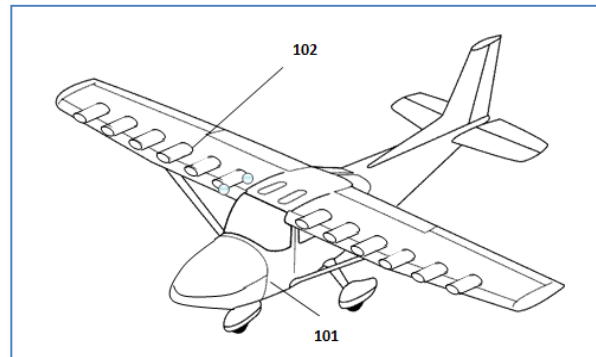
Our wind tunnel tests and analysis have shown lift coefficients > 10 , even without the use of flaps. With the addition of flaps, much higher lift coefficients are possible.

The thought of blowing air over the top surface of the wing is not a new concept, but one that is made practical by the use of distributed propulsion. In the past it has been tried with two propellers (e.g. the Custer Channel wing in the 1950s), two jet engines (the Boeing YC-14 in the 1960s) and with four jet engines (NASA's QSRA in the 1970s). These earlier efforts only provided improved aerodynamics over a small portion of the wing upper surface as they did not have distributed thrust capability. Further, the Boeing and NASA efforts used jet turbine engine exhaust air to enhance the aerodynamics. The very high velocity, very hot and extremely concentrated air made managing the aerodynamics difficult.

Here, with distributed electric propulsion, the success of these programs can be greatly leveraged with well distributed, near ambient temperature flows. Additionally, as will be described in the next section, the use of distributed propulsion adds many other benefits not realized in these earlier efforts.

The IDEAL Concept

IDEAL is the synergistic integration of multiple distributed electric ducted fans (EDFs) onto the aircraft structure to supply upper surface blowing over a substantial portion of the wing. This is shown schematically in a figure from the patent application. Here sixteen fans (102) blow air over the top surface of a typical light aircraft. Unlike the X-57 where a portion of the flow from each propeller goes under the wing, and the air swirling resulting in varying angles of attack along the wing span, this concept focuses all the flow over the top surface of the wing producing more lift per HP than possible otherwise.



While the EDFs provide thrust for the aircraft, they simultaneously provide increased lift coefficient over the wing, with minimal loss of thrust efficiency. Additionally, for landing, takeoff, or other situations needing very high lift at very low speed, flaps can be deployed on a portion of the trailing edge of the lifting surface. Upper surface blowing with flaps increases the lift even more dramatically than shown on the previous page as the air stays attached to the flaps due to the Coanda Effect.

Where a VTOL needs thrust more than 25% greater than the takeoff weight of the airplane ($1.25 * TOW$) to take off, with IDEAL very short take offs (less than 100 feet) can be achieved with thrust less than 30% of the weight ($0.30 * TOW$).

A control system can add a further novel and improved aerodynamics, by managing the individual EDFs. Sensing their state and that of the aircraft and surrounding air conditions; and comparing to the commands of a human pilot or an autopilot; internal logic allows:

- Varying the electrical power to the individual EDF or controlling nozzles associated with each of them, tailoring the spanwise lift distribution and thrust in real-time to control the airplane much as an aileron or wing warping.
- Real-time lift re-distribution to improve ride qualities through active gust alleviation. Here, accelerations to the airframe and relative wind angles can be sensed and the lift distribution changed to accommodate gusts reducing in accelerations and thus better ride qualities. Gust alleviation can also improve aircraft structure life by reducing the loads on the airframe.
- High system redundancy so the loss of single or even multiple EDFs can be compensated for by the redistribution of power to the remaining EDFs. This greatly adds to the safety of an electric airplane.
- Virtual elimination of stalls through three mechanisms: the higher velocity air over the upper surface remains attached to the surface greatly increasing the maximum angle of attack; the control of the EDFs can mold the lift distribution to avoid stalls; and the control system can sense pre-stall conditions and command power changes to effectively “control” away from the stall conditions.

- Cross wind compensation for greatly easing landing and taking off when the wind is not directly aligned with the runway by differentially altering EDF thrust.

Further:

- EDFs that are the right size and power are available, off-the-shelf.
- Each EDF and its controller weigh less than 1 kg (2.2 lbs) giving propulsion weight savings.
- EDFs and their controllers are far less expensive than traditional forms of propulsion.
- This concept marries very well with a hybrid power system. Such a system provides extended cruise time, high power for STOL and rapid climb out as well as back-up battery power in the event of the hybrid system IC engine failure.

Why This Technology is Important

This is an exciting time, reminiscent of the early days of aviation. There are new technologies and potential uses for them. Nobody is yet sure where it is all headed. Ideas for various forms of air taxis and personal aircraft abound. Many leverage on multi-copter configurations such as the EHang 184 and the Volocopter 2X, yet these are limited to short duration, with little reserve, using the current generation batteries and less than 30 minutes even with the most optimistic next generation batteries. Further, they offer no glide potential as a safety feature.

Other new concepts are based on VTOL where the propulsors and sometimes the wings transition from providing vertical thrust equal to the weight of the aircraft and payload to providing forward thrust for cruising. The transition from vertical to cruise has always been problematic for VTOL craft. That combined with multi-copter inefficiency during takeoff and landing is a drawback. Further, if these air vehicles are to be piloted, the demands on the pilots will be higher than on a traditional aircraft.

Vertical Take-off aircraft require thrust to weight ratios >1.25 . With IDEAL, near VTOL performance can be had with thrust to weight ratios of 0.3. There are two implications of this 4:1 ratio: 1) VTOL aircraft need bigger motors and circuits to carry more current with a high weight penalty. 2) During take-off, VTOLs use 4 times the energy as with IDEAL. (True it is only for a short time, but this still depletes the usable range of the airplane).

The vision of VTOL air taxis operating from driveways and roof tops is either a dream or a long way off. In reality, the ground and airspace needed for safe operation of VTOL and aircraft using the IDEAL technology are not much different.

To summarize, IDEAL offers:

- Leveraging the propulsors that already exist to get more lift with little thrust penalty
- Very very short take off distances
- Controllable spanwise lift distribution for improved ride qualities and safety
- Improved range

The Research and Development Plan

To better understand the potential and develop a workable IDEAL system, five tasks have been undertaken. All are works-in-progress, but the results to date, briefly described; demonstrate that what is claimed here is actually possible and practical.

Wind tunnel studies

While a number of different configurations have been sketched, the interaction between the propulsion and aerodynamics is sufficiently complex that analytical models cannot be used to optimize the system. Thus, wind tunnel test began in March 2016 to better understand the system. This work is in an open, 80mph, 2'x2' instrumented tunnel specifically built for this research. It has adequate Reynolds Number and turbulence to provide useful results. Many different models have been tested in the tunnel.



Wind tunnel



Pylon Mounted EDF



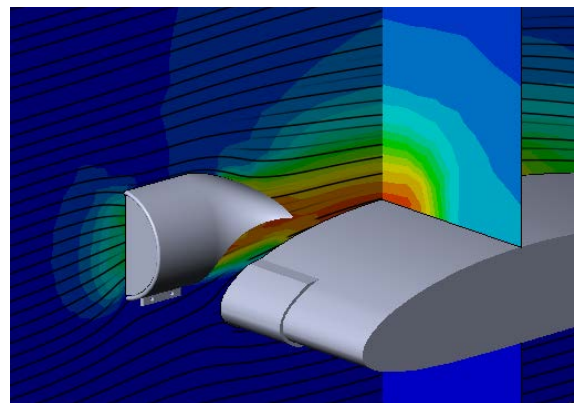
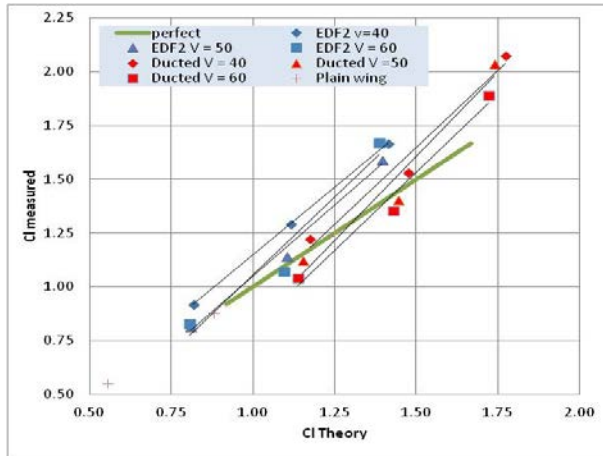
Directed Flow EDF

Wind tunnel testing is still in its early stages. However, early tests have shown lift coefficients greater than 10 even without the use of flaps.

Theory development

During the 1950s and 60s the British developed the basis for the analysis of upper surface blown configurations used here. These methods have been reduced to a computer code that has been used to analyze many different configurations.

The graph on the right shows the results of wind tunnel testing (vertical) versus the analytical model for lift coefficient over different speeds and angles of attack. The green line is perfect correlation. The similarity of the experimental results with the perfect correlation is encouraging. As more results from the Computational Fluid Dynamics (CFD) and wind tunnel are realized, this analytical model is being refined.



CFD studies

In parallel with the wind tunnel studies, Computational Fluid Dynamic models are being built. These serve two purposes. First, they help with the visualization of the complex flow. Second they guide the development of new wind tunnel models. This synergistic mix of testing, theory and visualization are leading to optimum configurations for the system.

Patent Application

A provisional patent application was submitted on Jan 1 2016. A full utility patent was submitted December 16 2016. This application has 15 claims and is under review by the U.S. Patent and Trademark Office.

Testing on Operational Aircraft

The modeling, wind tunnel testing and CFD studies are all aimed at developing configurations to be tested on a flight vehicle. In late 2016 a Jabiru J230 was purchased for these studies. It is being converted into a flying test bed so that EDF units can be externally attached to the upper surface of the wing, powered by batteries inside the cabin.



The J230 is ideal as it was originally designed as a four place aircraft and de-rated to a two-place to meet LSA rules. Thus, there is a large space aft of the seats and near the center of gravity for batteries and instrumentation. The EDF add-ons will be instrumented, as will the rest of the airplane, so that data can be taken on sets of EDF propulsors in full scale operation. Technology testing on this aircraft will begin in early 2018 and it will be renamed the “JabirWatt I”.

Initial testing will be with the stock wings and IC engine. A limited number of EDFs will be added to the wing, not enough to fully power the airplane but sufficient to verify the analytical modeling and scale wind tunnel results. Based on the success of the initial experiments on externally added EDFs, new wings will be designed and built to maximize the design, the IC engine will be removed and the plane will look more like the image below, the JabirWatt II.



The Needs

NASA is spending \$48M on the X-57 program. The effort described here, a larger jump in technology, is self-funded. However, to facilitate pushing this as far as it can go, with the goal of the design of an entirely new aircraft, the following is needed:

- Support for the JabirWatt I test program. This includes expenses for batteries and instrumentation.
- Improvement in the wind tunnel instrumentation. While the current facilities are sufficient, an upgrade could result in more accurate data.
- Development of the JabirWatt II. Using the Jabiru fuselage, custom wings will be designed and manufactured with the EDF systems built into the wings rather than added on to them as in the JabirWatt I. The IC engine will be removed and batteries installed to enable the airplane to reach its potential.
- Development of the control system. Part of the beauty of this concept is the abilities itemized on page three of this document. Building and testing this system will take technical expertise beyond the current capabilities.

- Optimization of the EDF propulsion units. Currently, many COTS units are available over a wide range of sizes and efficiencies. However, the performance of these units is not well optimized and their reliability suspect.
- Optimization of the EDF/wing configuration for maximization of overall efficiency, lift and thrust.

The Principals

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