Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Investigation of Distributed Electric Propulsion Use in Ultralight Aircraft

Master's Final Degree Project

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Supervisor

Kaunas, 2025

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Mechatronics (6211EX017)

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Task of the Master's Final Degree Project

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1. Title of the Project

Investigation of Distributed Electric Propulsion Use in Ultralight Aircraft

(In English)

Paskirstytosios elektrinės pavaros naudojimo ultralengvuosiuose orlaiviuose tyrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to investigate the feasibility of using distributed electric propulsion in ultralight aircraft.

Tasks:

1. to analyse the current use of electric propulsion in ultralight aviation and specificities of distributed electric propulsion;
2. to analyse the economical feasibility of using distributed electrical propulsion in ultralight aircraft.
3. to reveal advantages and disadvantages of using distributed electric propulsion compared to conventional aircraft configuration;

3. Main Requirements and Conditions

CFD analysis carried out of the conventionally powered ultralight aircraft and aircraft with distributed electric propulsion, upper wing surface pressure differences analysed – comparison of pressure (in Pa), lift and drag forces (in N).

4. Additional Requirements for the Project, Report and its Annexes

Not applicable

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Leonavičius Linas. Investigation of Distributed Electric Propulsion Use in Ultralight Aircraft. Master's Final Degree Project, supervisor Assoc.prof.dr. Darius Eidukynas; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: Distributed Electric Propulsion; Ultralight Aircraft; Electric Ducted Fans; all-electric aviation; upper surface blowing.

Kaunas, 2025. 52 p.

Summary

Purpose of this work was to evaluate the feasibility of using Distributed Electric Propulsion (DEP) as a single means of propulsion for ultralight aircraft. While some single seat aircraft that do not strictly fall into fixed wing ultralight category, but utilize DEP, are emerging, most of the current all-electric ultralight aircraft designs still use single propeller/motor configurations. Utilizing DEP has the potential to enhance lift by, depending on configuration, increasing the pressure on the upper surface of the wing and taking advantage of Coandă effect, or by Boundary Layer Ingestion (BLI). Different propulsor and placement options were analysed and preliminary configuration using four off-the-shelf Electric Ducted Fans (EDFs) positioned on the upper leading edge of the wing was proposed on the concept high-wing ultralight aircraft. Proposed configuration was based on the assumptions that providing direct airflow on the upper surface of the wing (Upper Surface Blowing) and utilizing Coandă effect will significantly increase the upper wing pressure, make the airflow more laminar and substantially increase the lift compared to conventional single propeller configuration. These assumptions were tested by carrying out Computational Fluid Dynamics (CFD) simulations using Ansys Fluent software. Results showed that even with lower total dynamic thrust of DEP configuration, it was able to provide noticeably greater lift compared to baseline single propeller configuration making it a feasible alternative. It was also noticed that nacelle geometry plays a big role in the pressure generation, initial assumption that open nacelles providing airflow on larger area of the wing were not proven. Further research on nacelle geometry was suggested, especially on closed high aspect ratio exit nozzles, as these could futher increase the lift. Lastly, economic considerations on using DEP were discussed. It was determined that overall aircraft costs would be higher due to the current high cost of larger diameter EDFs, however, it is feasible to utilize investments, common for electric aviation projects, for design and manufacturing stage and buyers could still be attracted by lower operating and maintenance costs, as well as improved aerodynamic characteristics.

Leonavičius Linas. Paskirstytosios elektrinės pavaros naudojimo ultralengvuosiuose orlaiviuose tyrimas. Magistro baigiamasis projektas, vadovas doc. dr. Darius Eidukynas; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: Paskirstyta elektrinė pavara; ultralengvieji orlaiviai; elektriniai kanaliniai varikliai; elektrinė aviacija; viršutinio paviršiaus apipūtimas.

Kaunas, 2025. 52 p.

Santrauka

Šio darbo tikslas buvo įvertinti galimybę naudoti paskirstytąją elektrinę pavarą (angl. Distributed Electric Propulsion, DEP) kaip vienintelę ultralengvojo orlaivio varomąją sistemą. Nors atsiranda vienviečių orlaivių, kurie, nors ir pilnai neatitinka ultralengvųjų orlaivių kategorijos reikalavimų, naudoja DEP sistemas, tačiau dauguma dabartinių visiškai elektrinių ultralengvųjų orlaivių vis dar naudoja vieno propelerio/variklio konfigūracija. DEP naudojimas turi potencialą padidinti keliamąją jėgą, priklausomai nuo konfigūracijos, didinant slėgį viršutinėje sparno dalyje ir pasinaudojant Coandă efektu arba ribinio sluoksnio įsiurbimu (angl. Boundary Layer Ingestion, BLI). Šiame darbe buvo analizuojamos įvairios pavarų ir jų išdėstymo galimybės, ir buvo pasiūlyta preliminari koncepcinio aukštasparnio ultralengvojo orlaivio konfigūracija su keturiais kanaliniais elektriniais ventiliatoriniais varikliais (angl. Electric Ducted Fans, EDF), išdėstytais ant sparno viršutinės priekinės briaunos. Pasiūlyta konfigūracija buvo paremta prielaida, kad tiesioginis oro srautas į viršutinį sparno paviršių (angl. Upper Surface Blowing) ir Coandă efekto panaudojimas žymiai padidins slėgį viršutinėje sparno dalyje, padarys oro srautą laminariškesnį ir reikšmingai padidins keliamąją galią, palyginti su tradicine vieno propelerio konfigūracija. Šios prielaidos buvo patikrintos atliekant skaičiuojamosios skysčių dinamikos (CFD) modeliavimą, naudojant „Ansys Fluent“ programinę įrangą. Rezultatai parodė, kad net esant mažesnei bendrajai DEP konfigūracijos dinaminei traukai, ji sugebėjo generuoti pastebimai didesnę keliamąją jėgą, palyginti su bazine vieno propelerio konfigūracija, todėl gali būti laikoma realia alternatyva. Taip pat buvo pastebėta, kad nacelės geometrija turi didelę įtaką slėgio generavimui – pradinė prielaida, kad atviros nacelės, nukreipiančios oro srautą į didesnį sparno plotą, būtų efektyvesnės, nepasitvirtino. Buvo pasiūlyta toliau tirti nacelių geometriją, ypač uždarų, didelio ilgio ir mažo išėjimo ploto angų (angl. high aspect ratio exit nozzles) efektyvumą, nes tai galėtų dar labiau padidinti keliamąją jėgą. Galiausiai buvo aptarti ekonominiai DEP sistemos naudojimo aspektai. Nustatyta, kad bendra orlaivio kaina būtų didesnė dėl šiuo metu didelių didesnio skersmens EDF įrenginių kainų, tačiau DEP technologiją būtų įmanoma finansuoti, pasinaudojant investicijomis, būdingoms elektrinės aviacijos projektams, ypač projektavimo ir gamybos etapuose, o pirkėjus vis tiek galėtų pritraukti mažesnės eksploatavimo ir priežiūros išlaidos bei geresnės aerodinaminės savybės.

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List of Abbreviations and Terms

Abbreviations:

ICE – Internal Combustion Engine;
DEP – Distributed Electric Propulsion;
STOL – Short Take-off or Landing;
PMAC - Permanent Magnet Alternating Current;
BMS – Battery Management System
BLDC – Brushless Direct Current
LSA – Light Sport Aircraft
MTOW – Maximum Takeoff Weight
MOGAS – Motor Gasoline
RC – Remote Controlled
AoT – Angle of Attack
USB – Upper Surface Blowing

Introduction

The aviation industry is undergoing a significant transformation due concern over carbon emissions and fuel costs. Electric propulsion for general aviation aircraft is being widely investigated as an alternative to conventional internal combustion engines. One of the approaches of electric propulsion is Distributed Electric Propulsion (DEP), which can offer potential aerodynamic and performance benefits. This project investigates the feasibility of utilizing DEP in ultralight aircraft, an aircraft category which is often overlooked in research and innovation. This aircraft category stands out with very stringent weight limitations, but reduced certification requirements for aircraft and pilot. Ultralight aircraft have traditionally utilized single small internal combustion engines, which are light and simple, but produce emissions, especially due to still widely used two-stroke engines and leaded gasoline. Some contemporary ultralight aircraft started using single electric engine/propeller configurations, however these do not deviate from standard conventional design and directly replace ICE to electric motor and gas tanks with batteries. DEP utilizes multiple smaller electric motors distributed across the aircraft wing and has the potential to improve aerodynamic characteristics, as well as introduce new design convention. Using Electric Ducted Fans (EDFs) in DEP further innovates the aircraft electric propulsion, as they are safe, efficient and offer freedom of installation. Main design considerations for using EDFs are size, quantity, position, installation method, nacelle design. Utilizing Coandă effect, which is described as tendency of a fluid (or gas) jet initialized tangentially on a curved surface to remain attached to that surface, also becomes a design objective. Properly utilized Coandă effect improves aircraft lift parameters, reduces take-off/landing distances and reduces stall speed. Economic feasibility of DEP in the ultralight category remains a subject of discussion. While the maintenance and operational costs are assumed to be lower compared to ICE aircraft, but the upfront costs may result in cost-sensitive recreational pilots and small operators being hesitant to transition to all electric aircraft even with noticeable aerodynamic improvement. Computational Fluid Dynamics (CFD) is used to simulate the aerodynamic characteristics and will be used to compare the upper wing pressure, lift and drag between conventional single engine/propeller configuration and DEP configuration using EDFs on the same concept high-wing ultralight aircraft.

Aim: to investigate the feasibility of using distributed electric propulsion in ultralight aircraft.
Tasks:

1. to analyse the current use of electric propulsion in ultralight aviation and specificities of distributed electric propulsion;
2. to analyse the economical feasibility of using distributed electrical propulsion in ultralight aircraft.
3. to reveal advantages and disadvantages of using distributed electric propulsion compared to conventionally powered aircraft.

Hypothesis: Distributed electric propulsion is a feasible alternative to conventional single propeller configuration.

1. All Electric Aviation – Situation Analysis

Concerns due to greenhouse gas emissions call for more widespread adoption of electric energy in the transportation sector, which currently consumes most of the fossil fuels [1]. As a result, the transportation sector is responsible for a staggering 28% of carbon dioxide CO2 emissions [2]. In the aviation sector, various regulations are put into force, such as EU ETS (European Emission Trading Scheme) and CORSIA (Carbon offsetting and reduction scheme for international avaition) [3], which introduce allowable emmisions ceiling for aircraft and carbon-neutral growth goals combining technological inovations, economic measures and alternative energy sources (Fig 1.).

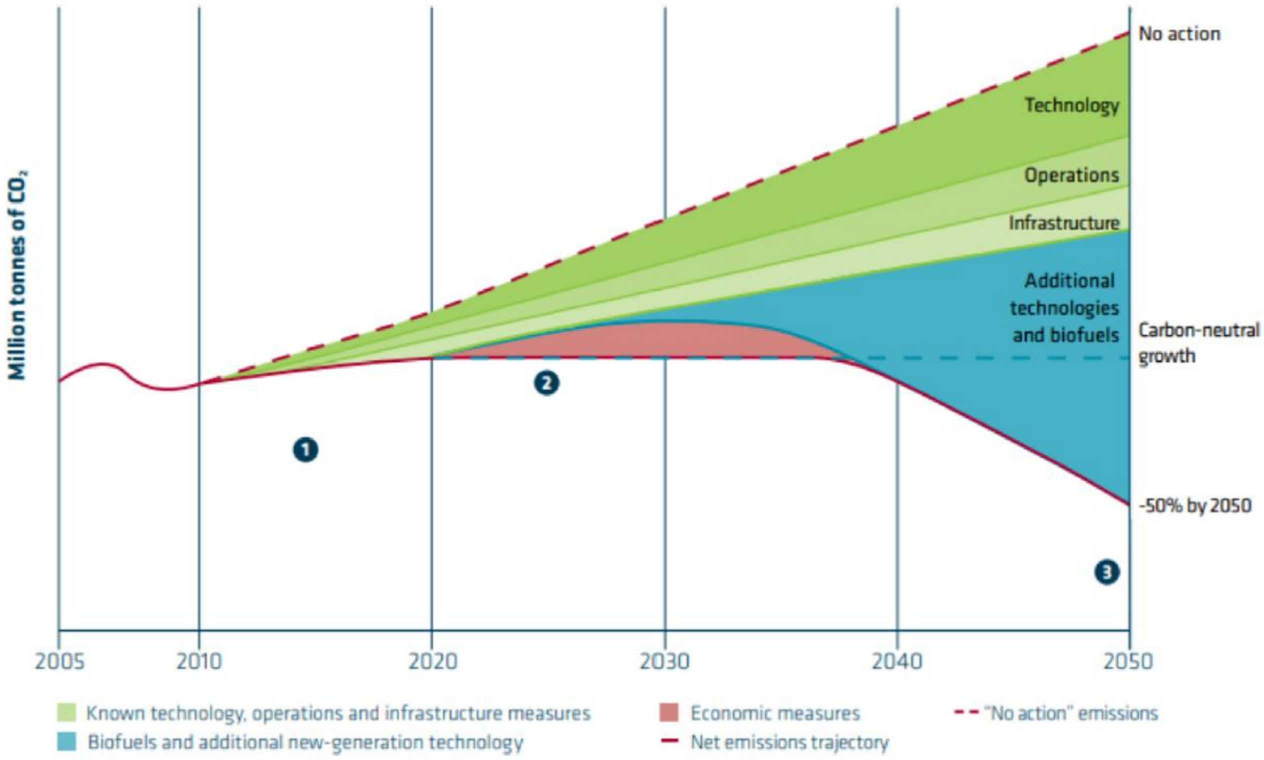


Fig. 1. Aviation emissions reduction goals [2]

Such regulations and goals are mostly targeted at large commercial aircraft, however light aviation is under scrutiny as well since light aircraft still use highly toxic leaded fuel, while the lightest aircraft class (ultralight aircraft) mostly utilize two-stroke ICEs with oil added directly to the fuel mixture and resulting in greater amount of remnant gases being forced into the exhaust [4]. To combat the unavoidable emissions of using fossil fuels, designs of all electric aircraft need to be produced.

The biggest challenge in electric aviation is the low energy density of the batteries and resulting limitations of distance travelled [5]. Current battery technology can produce up to 400 Wh/kg energy density [6], while MOGAS used in light/ultralight aviation has an energy density of around 12000 Wh/kg greatly exceeding the maximum energy density possible for current batteries. Emerging Li-O_2 (approx. 3400 Wh/kg energy density) and Li-S (approx. 1000 Wh/kg) [1] technologies would improve the situation, but Li-ion batteries producing 250-340 Wh/kg are the most used and accepted technology today (Fig. 2).

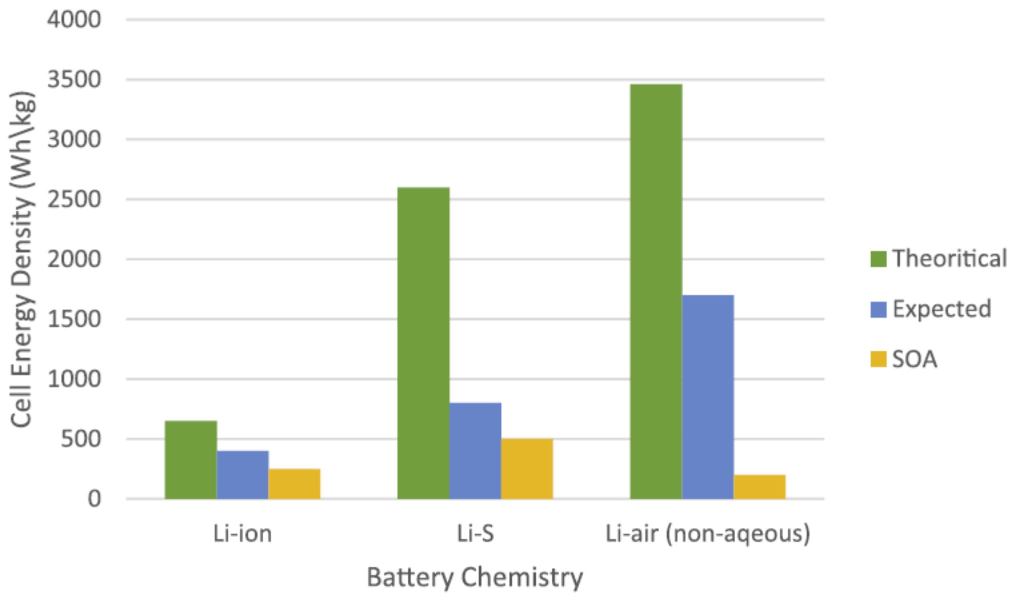


Fig. 2. Comparison of energy densities of battery chemistries potential for aviation applications [6]

Considering the major limitation of energy density of the batteries, design objectives for all electric aircraft are decreasing the mass, decreasing the drag force and increasing the lift force [5]. This is relevant for all aircraft, but especially for all electric configurations, since power required for electric aircraft directly depends on its weight (Fig. 3). Hence as ultralight aircraft class is intrinsically very heavily limited on weight, it is potentially most suitable to offset the battery limitations.

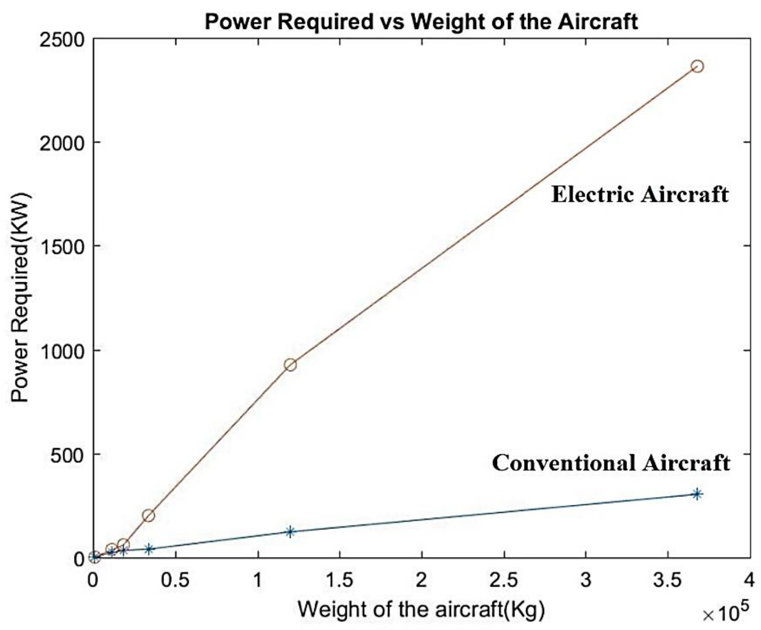


Fig. 3. Power required vs. weight of the aircraft [1]

Ultralight aircraft (definition presented in Table 1) are generally used for recreational purposes and in many countries do not require type certification or a pilot’s license. Such aircraft not requiring certification provides a noticeable advantage of being able to iterate the design without going through the stringent validation process. Also, as such aircraft are intrinsically used for short flight periods, the drawback of distance travelled limitations is less noticeable compared to heavier aircraft.

Additional advantages of ultralight aircraft are low fuel consumption, lower operating costs, ability to utilise smaller airfields and landing strips. Lastly, their simplicity in design and operation results in easier maintenance.

Table 1. Ultralight Aircraft Definition [7 –10]

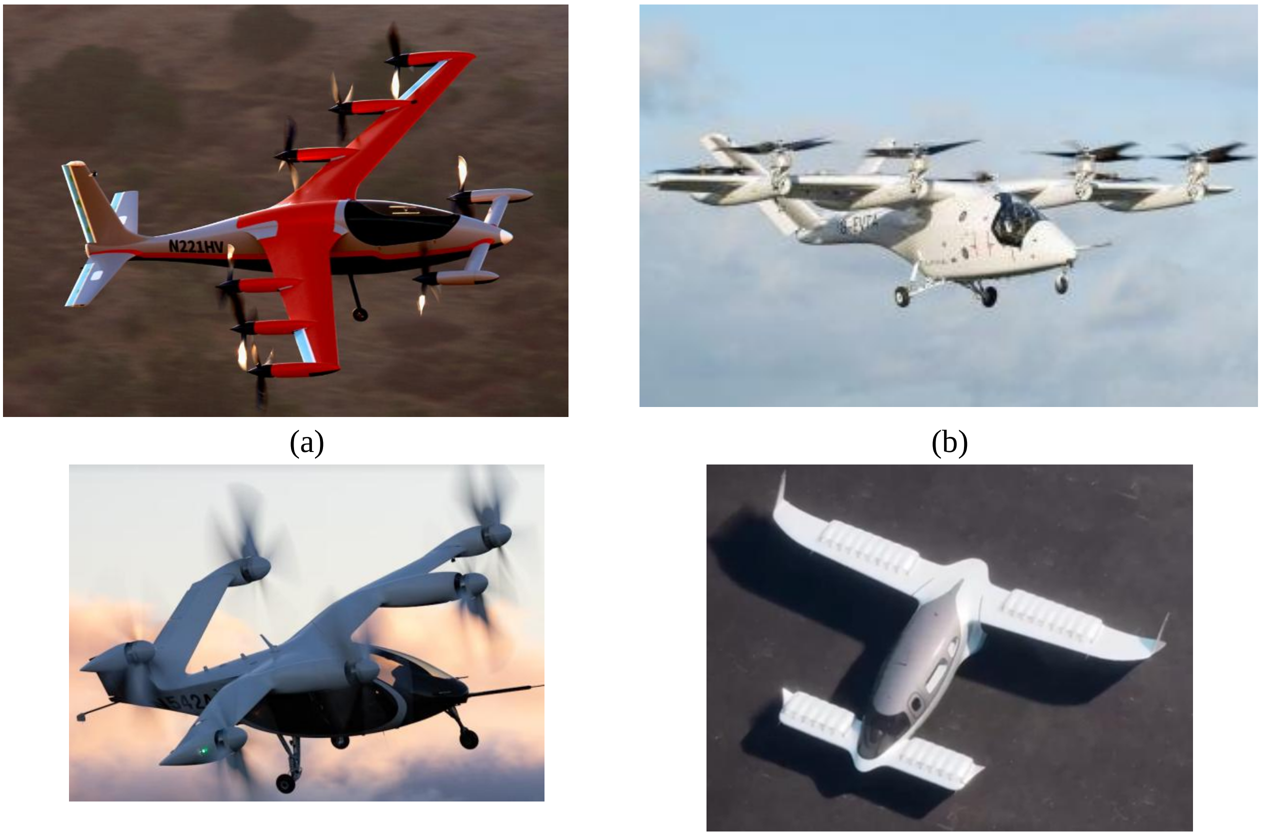
	FAR Part 103 (US)	**ULM single-seater multiaxis (France)**	**Single Seat Deregulated Microlight (UK)**	**Simple aircraft "Paprastieji orlaiviai" (LT)**
Max Empty Weight	115kg (254lb)	223kg	N/A	120kg
MTOW	N/A	330kg	300kg	N/A
Fuel, max	19 liters (5 U.S. gallons)	30 liters	N/A	15 kg
Airspeed	Max 55 knots in level flight	N/A	N/A	N/A
Max Power	N/A	35 kW	N/A	N/A
Stall speed	Max 24 knots	Max 38 knots	Max 35 knots	45 km/h

As noticed previously, one of the main design objectives for all electric aircraft is to increase the lift force. Utilising all electric propulsion helps to achieve this goal since propulsors can be separated from batteries (no need for fuel lines as in conventional aircraft) offering more freedom in their number, size and placement [11]. Distributed propulsion is considered a promising field for achieving more powerful and high-performance electric aircraft. The two most common distributed propulsion techniques used are Distributed Electric Propulsion (DEP) and Turbo-electric distributed propulsion (TeDP) [6]. DEP can be achieved by using multiple small electric motors to accelerate airflow. Unlike conventional propulsion configurations where large engines produce concentrated thrust vectors, the thrust force in DEP is distributed about the airframe using smaller motors to maximize the aerodynamic efficiency [6].

Fig. 4. NASA X-57 Maxwell DEP aircraft [6]

Placing multiple propulsors at leading edge of the wing increases dynamic pressure on the airfoil at low speeds improving the STOL performance, augments the lift and enables smaller wing surfaces to achieve high lift [6, 11]. Such configuration is recognizable on NASA X-57 DEP aircraft (Fig. 4) utilizing technique called Leading-Edge Asynchronous Propellers Technology (LEAPTech) [11]. Placing propulsors at the trailing edge results in Boundary Layer Ingestion (BLI), which improves the aerodynamic performance in cruise flight [11]. BLI is mainly based on flux re-acceleration on the airfoil due to boundary layer engine ingestion, which leads to a wake reduction and less power required by the engine [12]. Most modern application of BLI is electric vertical take-off and landing (eVTOL) aircraft Lilium (Fig. 5).

EVTOLs are currently widely researched and developed technology. Development of such aircraft stems from the wider field of Urban Air Mobility (UAM) which tries to tackle transportation needs for growing urban populations [13]. While most of the developed eVTOLs are designed as means and part of the transportation service infrastructure, the aircraft themselves are utilizing design principles never used in mass production civil aircraft, including distributed propulsion systems. Notable eVTOLs KittyHawk, Vertical Aerospace VX4, Joby and Lilium (Fig. 5) utilize DEP with different approaches. The most outstanding design is Lilium aircraft with a tandem wing, no AFT stabilizers and with multiple electric ducted fans (EDFs) taking advantage of BLI. While emerging eVTOL designs almost exclusively use DEP, almost none of the existing ultralight aircraft have this as part of their construction



(a) (b)

(c) (d)

Fig. 5. (a) KittyHawk (b) VX4 (c) Joby (d) Lilium [14-17]

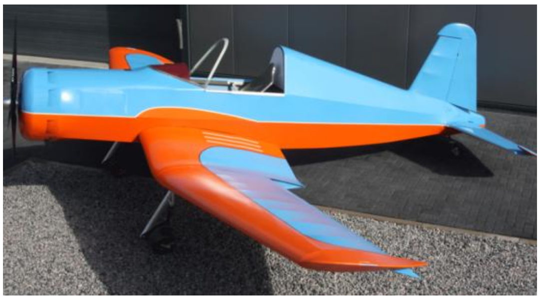
1.1. Current Status of All Electric Ultralight Aviation

There are several existing ultralight aircraft designs with fully electric propulsion systems, few examples provided in Table 2 and Fig. 6. These ultralights are almost direct conversions of their ICE variant counterparts featuring single motor/propeller configuration. However, new systems such as BMS and electric throttle control still must be introduced

Table 2. Electric propulsion ultralight aircraft [18-22]

	Corsair e-motion	**Aerolite EV-103**	**Electric Zigolo**	**E-Spyder**
Wing span	24,6 ft	26 ft 10.25 in	37 ft	33.1 ft
Length	20,7 ft	16 ft 3.25 in	18 ft	19.4 ft
Wing area	108 sq. ft	121 sq. ft	161 sq. ft	
Empty weight	177 lbs (without batteries)	-	-	410 lbs
Payload	375 lbs	-	-	-
Safe loading	+6g / -4g	+4g / -2g	-	-
Engine	Electric motor HPD20	Sensorless brushless PMAC motor	-	-
Power	30 kW peak / 20 kW continuous	25 kW peak / 20 kW continuous	28 kW peak / 20 kW continuous	24 kW
Batteries	7, 10 or 14 kWh, max 136 lbs	10.4 kWh (four batteries, 2.6 kWh each)	6.2 kWh (two batteries), 66 lbs	13 kWh
Flight time	Up to 2 hours (14 kWh)	40 minutes	45-50 minutes	60-90 minutes
Take off roll distance	<130 ft	100 – 200 ft	-	-
Stall speed	44 km/h (FAR 103 version)	42 – 45 km/h	35 km/h	-
Cruise speed	100 km/h (FAR 103 version)	65 – 72 km/h	73 km/h	61 km/h
Maximum speed	102 km/h (FAR 103 version)	101 km/h	95 km/h	109 km/h
Best climb speed	6 m/s (FAR 103 version)	2.45 – 3.3 m/s	-	-
Vr (rotation speed)	-	48 km/h	-	
Price	-	34900USD	-	39990USD

Completely novel ultralight aircraft designs are emerging as well that do not fall into the conventional single fixed wing configuration. Aircraft like Jetson One and BlackFly (details provided in Table 3 and Fig. 7) offer a completely new approach to single-seat aircraft. Both of these aircraft have VTOL capabilities and fly-by-wire controls, and in the case of Jetson One, it does not have fixed wings to provide the lift - the lift is only generated and flight control being exerted via the propulsors themselves. Such configurations reduce the flight endurance significantly compared to fixed wing aircraft. In the case of BlackFly, it features a fixed tandem wing with no vertical stabilizers. This is a very unusual configuration only possible utilizing DEP. Having a flight range of 20 miles, it’s also a very short-endurance aircraft. Designs such as these are a step in the direction of all-electric single-seat aircraft, however, the endurance remains a major issue.



(a)

(b)

(c)

(d)

Fig. 6. (a) Corsair (b) Aerolite EV (c) Electric Zigolo (d) E-Spyder [18-22]

(a)

(b)

Fig. 7. (a) Jetson One (b) BlackFly [23, 24]

Table 3. Jetson One and BlackFly parameters [23, 24]

Parameter	**Jetson One**	**BlackFly**
Empty Weight	40kg kg / 88lbs	348 lbs
Weight with pilot	181kg / 399lbs	578 lbs
Size	2480 x 1500 x 1030 mm	13 ft 7 in x 13 ft 7 in x 5 ft 3 in
Flight time/ range	20min	20 miles
Max Flight speed	102 km/h	-
Cruise speed	-	60 mph
Max. climb rate	-	490 fpm
Max. descent rate	-	540 fpm
Flight controls	3 axis joystick, throttle lever	Joystick, fly-by-wire controls
Batteries	Lithium-Ion	8kWh
Power	88 kW	-
Motor	Electric brushless outrunner	8 fixed propulsion units
Chassis	Aluminium	Epoxy-impregnated carbon fiber

Parameter	Jetson One	BlackFly
Static thrust	-	960 lbs max
Price	98000USD	-

1.2. Chapter Summary

Battery energy density is the most limiting factor in electric aviation and the purpose of DEP is to maximize the aerodynamic characteristics to offset this limitation. DEP is mostly utilized in eVTOLs with different configurations (trailing/leading edge propulsor placement, open propellers/EDFs, tandem wing/conventional fixed wing configurations). While some single seat aircraft starting to utilize DEP in very novel designs, most electric ultralight aircraft still use single propeller/motor configurations almost identical to their internal combustion engines variants.

2. Ultralight Aircraft With Distributed Electric Propulsion – Justification and Methodology

2.1. Control and Management Systems of Electric Propulsion

In the most basic fully electric aircraft two control/management systems are present: throttle control and battery management system. Throttle control for commonly used Brushless Direct Current (BLDC) motors is carried out through the motor controller which provides current pulse to the motor stator windings to have control over the speed and torque [25].

BLDC motors can be sensorless (as in Aerolite EV-103) or with Hall Effect sensors. Hall Effect sensors directly detect the rotor angle of the rotating part, while sensorless motors/controllers measure the back electromagnetic force (EMF) within the non-driven coils to gather the position of the rotor using estimation algorithms and control tools [25]. There are several advantages and disadvantages of using sensorless motor/controller configurations, advantages being that deviations of current and thrust characteristics that BLDC motors with sensors sometimes display can be avoided, while the disadvantage is that sensorless configuration is generally more complex and uses estimation algorithms compared to actual readings, even though has been proven to show good response at various speeds [25]. Both motor configurations (with sensors and sensorless) can be used for ultralight aircraft applications and do not introduce significant advantages or disadvantages over the other.

Other component in the control system is the controller. DEP requires a more advanced controller unit capable of managing multiple motor inputs and outputs, but the principle control scheme remains similar. Researchers proposed a hybrid-electric powerplant scheme [26] which can be adapted for all electric one by just omitting the conventional powerplant component (Fig. 8).

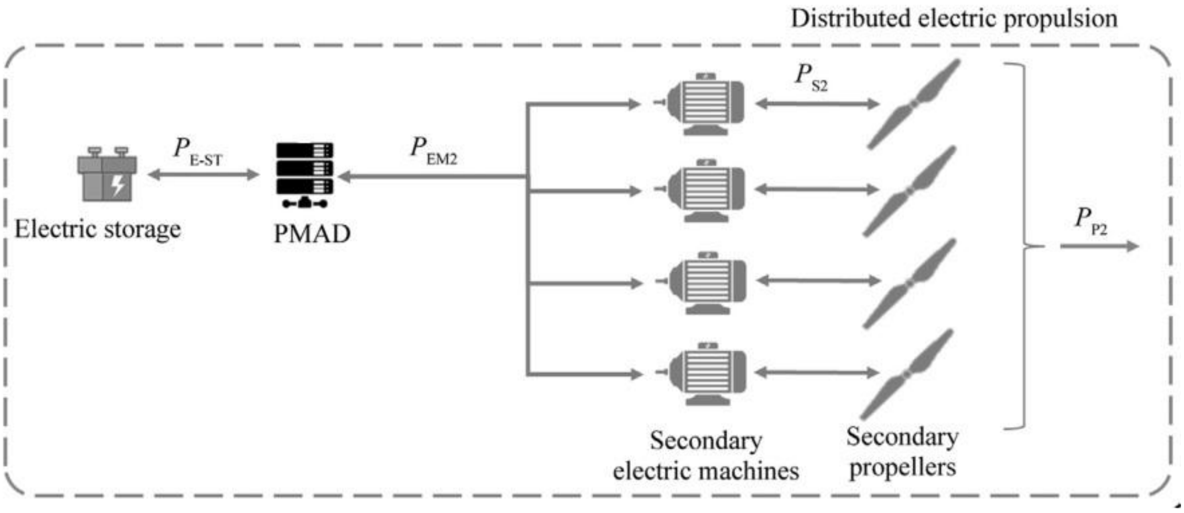


Fig. 8. Adapted DEP scheme [19]

Propulsion and control power is drawn from the on-board batteries that need to be managed by Battery Management Systems (BMS). BMS is required to track the status of the battery so that safety of the flight could be ensured. Researchers outlined the main parameters that the BMS must keep track of: voltage, temperature, current, state-of-charge and state-of-health [27]. Block diagram of BMS is provided in Fig. 9.

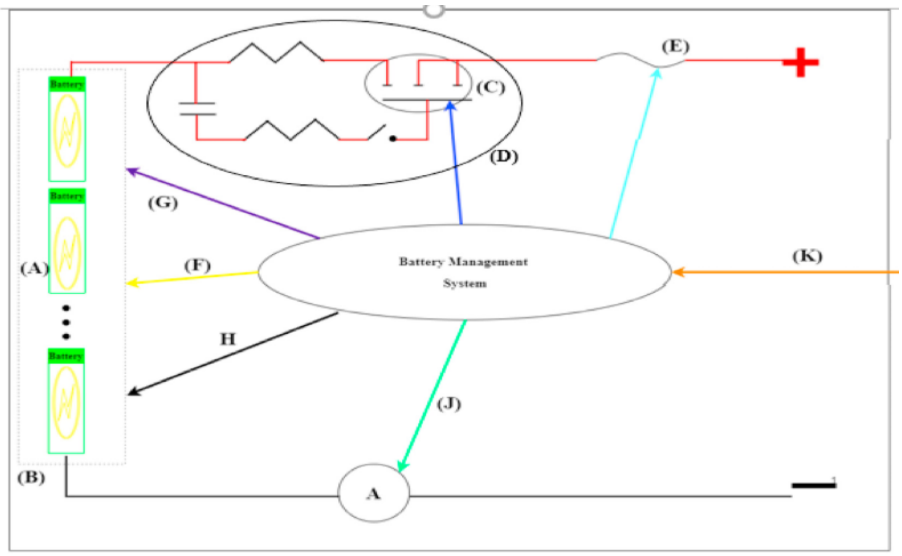


Fig. 9. BMS block diagram: (A) Battery cell, (B) Battery pack, (C) Mosfet, (D) Cell Balancing (E) Fuse, (F) Battery cell voltage measurement, (G) Battery Cell temperature measurement, (H) Battery pack vibration and pressure measurement, (F) Current measurement, (K) Communication [27]

BMS monitors and regulates charging and discharging processes of the battery, as well as the detection of battery type, voltages, temperature, capacity, state of charge, power consumption, remaining operating time, charging cycles, and other characteristics. BMS also provides a cell balancing function, to ensure that different battery cells have the same charging and discharging requirements. Various commercially available BMS microprocessors can be used together with lithium-ion batteries, such as those offered by Linear Tech, Analog Devices, Texas Instruments and other brands [27]. These microprocessors provide various features and communication protocols to interface with the battery and the system. It is essential that the status of the battery is communicated to the pilot at all times, so that they can monitor the performance and health of the battery and take appropriate actions if needed. Therefore, a BMS is a vital component of any lithium-ion battery-powered system.

2.2. Yaw, Pitch and Roll Controls

While throttle control for DEP can be achieved via fairly simple scheme, yaw, pitch and roll controls for DEP introduces completely new considerations. There are several possible control schemes provided in Fig. 10. It must be noted that utilizing DEP brings fourth additional possibility of controlling the aircraft via propulsion. The idea of Propulsion-Controlled Aircraft (PCA) is to utilize the thrust force vector applied at a distance from the aircraft centre-of-gravity by the individual aeroengines to produce a moment and associated angular acceleration [28]. Electric propulsors exhibit significantly shorter time interval between the throttle input and resulting thrust output hence are much more feasible to be used for PCA compared to ICE, however aircraft stability and control reliability is still a concern [28]. Researchers noted that a complex digital engine control system including digital twins of engines, diagnostic and prognostic component as well as thrust vectoring might be in order to achieve required stability requirements [28]. Systems such as this are more feasible for heavier aircraft which already utilize digital flight law systems and less so for ultralight aircraft.

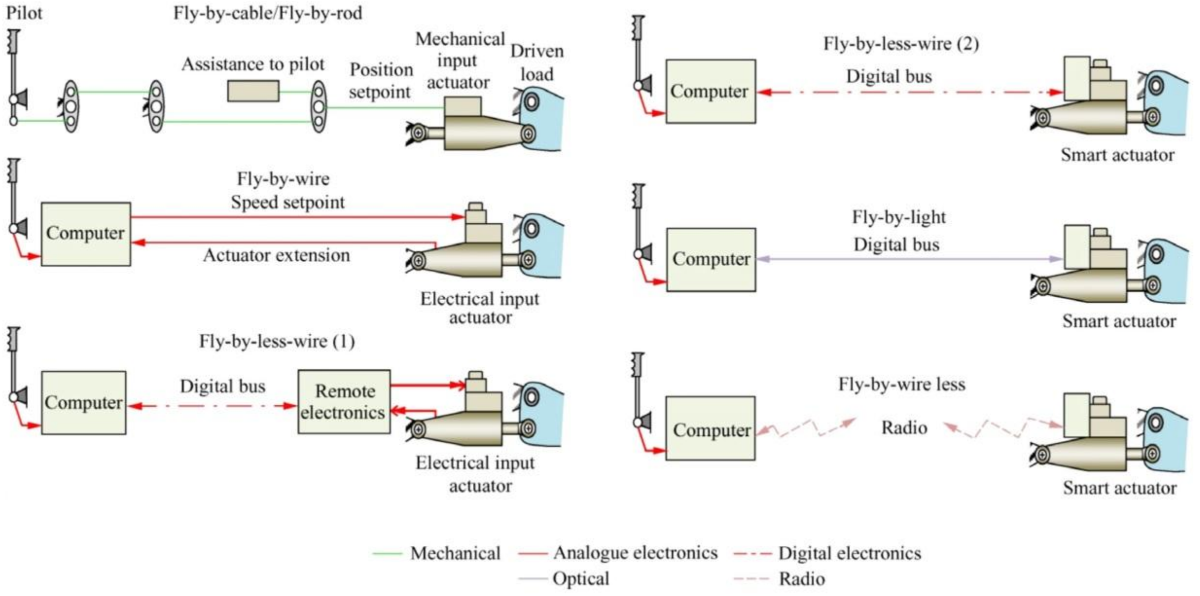


Fig. 10. Flight control schemes [28]

Conventional ultralights use fly-by-cable scheme as it's fairly simple, well understood, the distance between the pilot inputs and control surfaces is low, inexpensive and it does not require computers and any additional power sources for actuation. These features are all critical for keeping the ultralight aircraft weight, price and electric power consumption as low as possible. Additionally, the issue of electric actuation of control surfaces reliability has to be considered, the required fault-tolerant power electronics, redundant electronics/motor architectures [26] further increase the weight, price and power consumption, hence the fly-by-cable is possibly still the preferred control scheme for ultralight aircraft with DEP.

2.3. Propulsors, Their Size, Quantity and Placement

The two main propulsor variants that can be used for electric all-aircraft are propeller/motor combination and Electric Ducted Fans (EDF). For most ultralight aircraft configurations open propellers installed on the leading edge of the wings are intrinsically unsafe because the blades interfere with the pilot when getting to and out of the seated position. Open propeller installation on the trailing side of the wing (pusher configuration) is feasible and quite common in ultralight aircraft (Zigolo, Aerolite in Fig. 6). Such installation offers the advantage of not obstructing the pilots view and in certain configurations could result in boundary layer ingestion which theoretically improves the cruise flight performance [11]. However, there are noticeable disadvantages of pusher configuration: it is much more difficult to cool the engine as propeller does not provide a direct air stream on it, also for ultralight aircraft pusher configuration incurs a weight balancing issue when on ground (pilot acts as a ballast to lift the tail from the ground). Additionally, air flow is not obstructed by the wing and fuselage for propellers in tractor configuration hence increasing the freestream velocity [29]. Considering the mentioned advantages and disadvantages, tractor configuration is preferred for ultralight aircraft design.

It must be noted that researchers studied the aerodynamical effect on wings when using multiple propeller/engine nacelles integrated to wings in distributed propulsion and compared it to single larger nacelle (baseline configuration) (Fig. 11). Results showed that distributed propulsion option had reduced drag force, however demonstrated significantly reduced lift force due to the reduced effective wing area and the blockage effect of the engine nacelles [30], hence the proposed design would have to be optimized for better results.

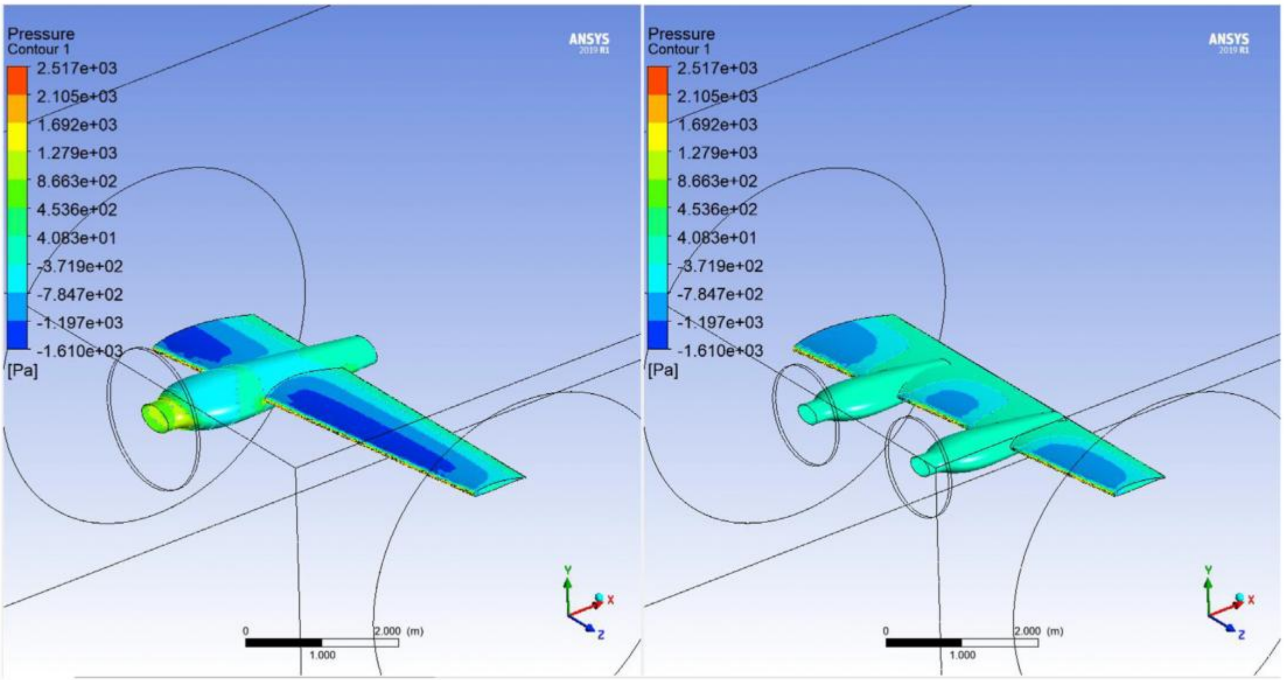


Fig. 11. Wing Pressure distribution (left: baseline configuration, right: distributed propulsion) [30]

Installation of EDFs on the leading edge of the wings does not have intrinsic safety issues due to the blades being fully enclosed in the outer casing. Ducted fan engines have been used for aircraft propulsion since 1932, subsequent studies concluded that ducted fan engines have higher static thrust force compared to open propellers of the same diameter and power loading [31]. There were several transport aircraft such as Boeing YC-14, AN-72 and NASA QSRA (Fig. 12) designed in the 1970s utilizing overwing ducted fan engines for Upper Surface Blowing (USB). Purpose of the USB is to take advantage of the Coandă effect which is described as the tendency of a fluid (or gas) jet initialised tangentially on a curved surface to remain attached to that surface [32].

(a)

(b)

(c)

Fig. 12. Overwing engines (a) YC-14 (b) AN-72 (c) NASA QSRA [33 - 35]

Airflow attached to the upper surface of the wing increases pressure and subsequently – lift force. For overwing engine installation, this significantly improves the STOL performance. Contemporary attempt to use EDFs to harness the Coandă effect is the JibirWatt aircraft (Fig. 13).

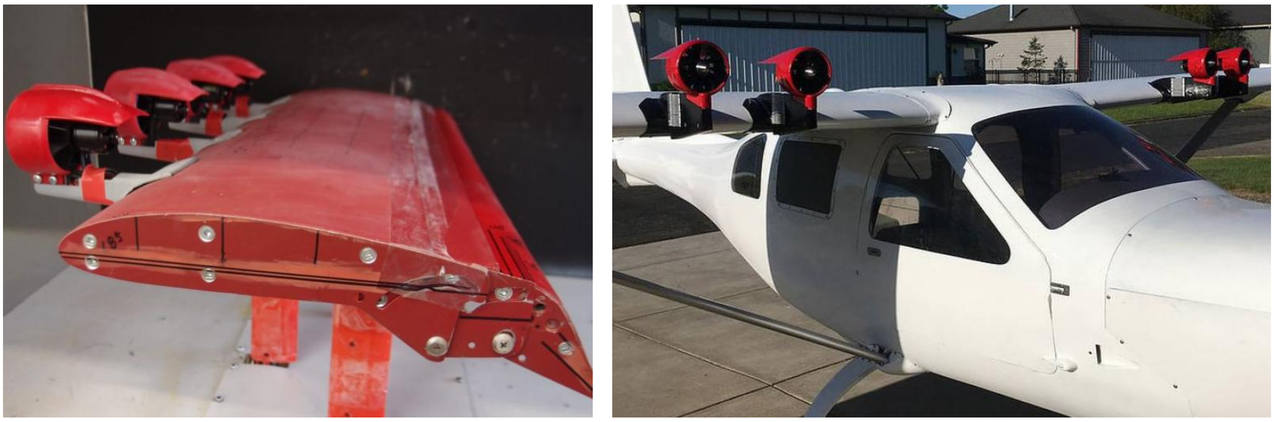


Fig. 13. JabirWatt EDF installation [36, 37]

JibirWatt is a hybrid electric aircraft which is a modified Jabiru J230-D, a two-seat LSA with original Jabiru 3300 ICE and integrated four 120mm diameter overwing EDFs [37]. Testing has shown that introducing EDFs significantly decreased stall speed, decreased take-off distance potential as well as increased all features of the lift curve (Fig. 14) among other benefits. Additionally, such configuration does not appreciably reduce effective wing area and does not block airflow onto the wing, hence not reducing the lift force as noted previously by researchers investigating multiple nacelle integration directly to the wing [30].

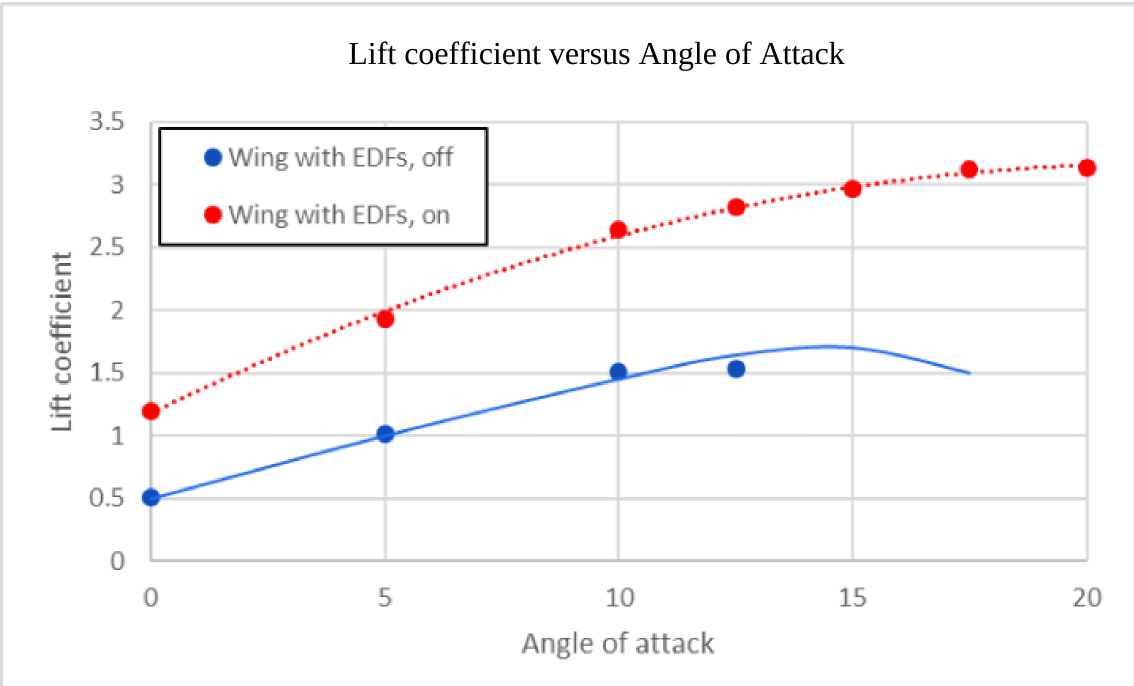


Fig. 14. JabirWatt Lift curve [37]

JibirWatt utilizes open exit nozzle for it's EDFs as shown in Fig. 13. Researchers studied various USB exit nozzle geometry configurations (Fig. 15) and their effect on lift enhancement [38-39]. It was concluded that increasing the aspect ratio of the nozzle plays a predominant role in lift enhancement [38].

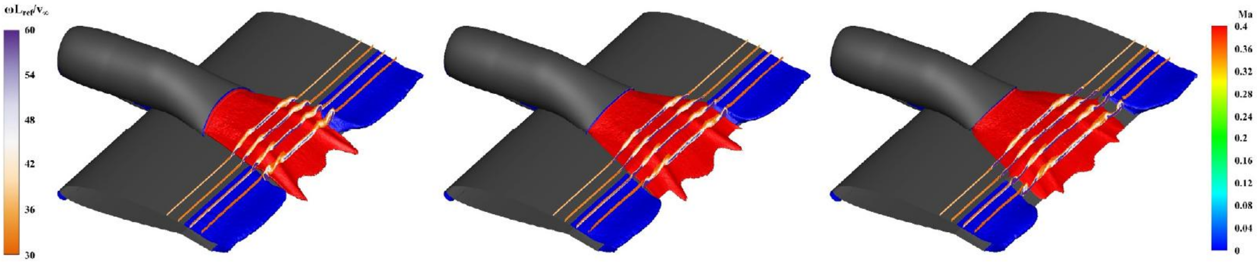


Fig. 15. Different exit nozzle configurations [38]

However, it is considered that closed large aspect ratio nozzles are mainly required to maintain thrust at higher speeds while having an additional benefit of alleviating flow separation. Flying at low speeds JibirWatt open exit nozzle is presumably more advantageous because it provides direct air flow to a larger area of the wing, hence increasing the lift without high speed.

Optimal quantity of engines is another topic of research. Scientist suggested a design rule to be used in early design stages and to maximize the aircraft overall efficiency in cruise which was derived from the application of first principles, allometric scaling and dimensional analysis [11]. This rule states that the optimal number of propulsors increases with aircraft mass to the power of 0.29. This rule will be tested in methodological part of this work, however it must be mentioned that it mostly applies to heavier aircraft and the results might not be directly suitable for ultralight designs.

Battery placement also carry a significant impact on the all electric aircraft design. Existing all electric ultralights usually replace gas tank for batteries in the same location (Fig. 16) which does not require re-evaluation of aircraft weight and balance.

(a) (b)

Fig. 16. Gas tank and battery location (a) Aerolite 103 (b) Aerolite EV-103 [19]

Designing all electric ultralight allows for freedom of battery placement and taking commercial airliners as template – wings would provide the best location. There are numerous advantages of placing the batteries in wings such as decreasing the wing loading when under lift force, increasing the wing stability, improving the weight and balance of the aircraft (battery mass closer to the airfoil aerodynamic centre) avoiding unwanted moments.

2.4. Chapter Summary

For ultralight aircraft is preferred to do without complex fly-by-wire control schemes as these increase the weight and price, only electrical systems required are throttle control and battery management systems for DEP usage. Propulsor quantity, placement and size plays a major role in the construction and aerodynamic performance of an aircraft, especially when utilizing Coandă effect and optimizing exit nozzle geometry for EDFs. Additionally, using electric propulsion can take advantage of constructional benefits such as freedom of placement of propulsors and batteries, depending on which the weight and balance can be improved, as well as wing loading parameters.

3. Ultralight Aircraft with Distributed Electric Propulsion – Preliminary Design and Simulation

This part of the study will propose general design features of the ultralight aircraft with DEP utilizing EDFs and will evaluate aerodynamical advantages (if any) comparing it to baseline variant with single motor/propeller of the same aircraft. Main parameters and reasoning of preliminary ultralight aircraft are provided in Table 4.

Table 4. Investigated ultralight aircraft parameters

Parameter	Value	Reasoning
Max Empty Weight (MEW)	115.21kg (254lbs)	FAR Part 103 requirements
Weight reserved for fuel	13.63kg (30 lbs)	5 US gallons (FAR Part 103) * 0.72 kg/l (MOGAS)
Pilot‘s weight	100kg (220.46 lbs)	Assumed conservative weight
Payload	20 kg (44.09 lbs)	Assumed weight
Max Take-off weight (MTOW)	250kg (550 lbs)	Rounded sum of MEW and fuel, pilot, payload weights. MTOW is in line with similar ultralight aircraft.
Airspeed	Max 55 knots in level flight	FAR Part 103 requirements
Stall speed	Max 24 knots	FAR Part 103 requirements
T/W (Thrust to Weight ratio)	0.375	Median value taken of T/W ratio for general aviation aircraft [53]
Required Thrust	93.75kg (206.68 lbs)	Based on T/W (static thrust / MTOW)
Cruise speed	70 km/h (19.4 m/s)	Based on similar aircraft per Table 2.
Cruise altitude	700 meters	Assumed altitude commensurate with aircraft type
AoT	0deg in cruise flight	Assumed angle of attack

3.1. Baseline Configuration

Baseline configuration is an existing concept standard single engine/propeller tractor ultralight design similar to E-spyder (Fig. 6). Two blade 1.5m diameter carbon propeller is selected for baseline configuration with 2500 RPM (cruise). General baseline configuration is presented in Fig 17, Fig 18 and Table 5.

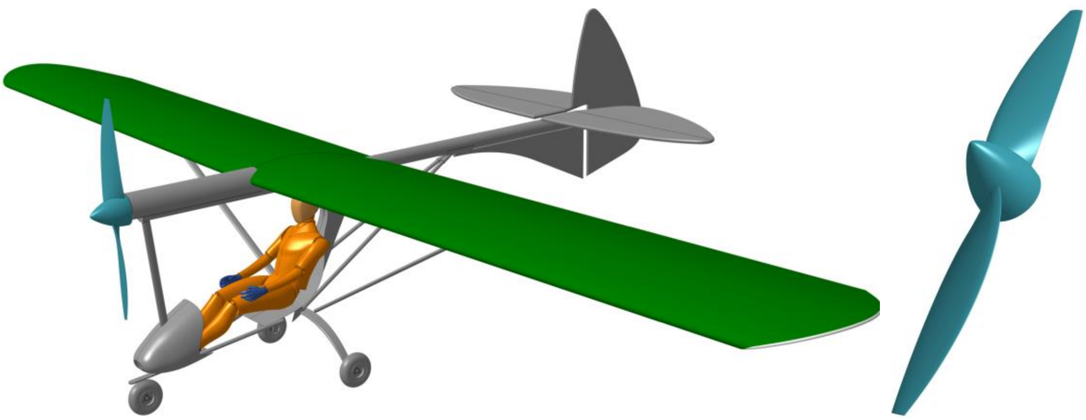


Fig. 17. Baseline configuration and propeller

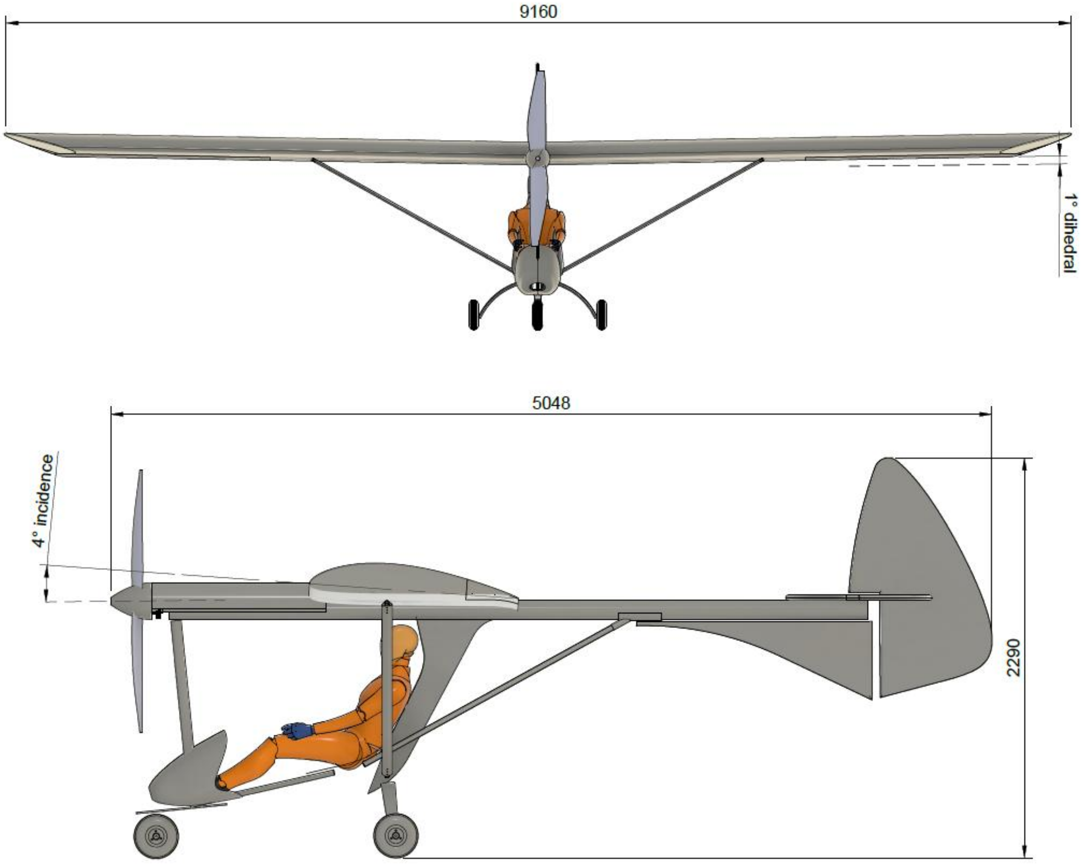


Fig. 18. General geometry (dimensions in mm)

Table 5. Wing geometry

Parameter	**Value**
Wing span	9.16 m
Wing area	10.063 m^2
Aspect ratio	8.338
Dihedral	1 deg

Selected airfoil is LAP00-137 [40] presented in Fig. 19

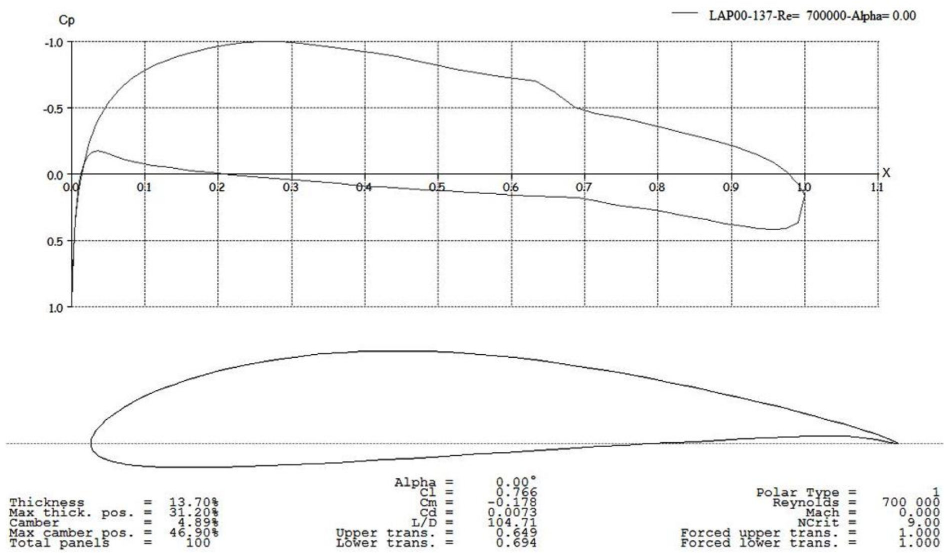


Fig. 19. LAP00-137 Airfoil [40]

3.2. DEP Configuration

This section will define target DEP aircraft configuration. Main features that need to be investigated are configuration type (tractor or pusher), type of propulsors, size and quantity of propulsors and propulsor installation location.

3.2.1. DEP Configuration – Main Configuration Type and Type of Propulsors

Main configuration types, briefly discussed in previous chapters, are tractor and pusher configurations and are both feasible for ultralight aircraft with DEP offering different advantages and disadvantages. Summary of the considerations for pusher and tractor configurations is presented in Table 6.

Table 6. Possible propulsor locations and types.

Image	Configuration	Comments
	Propeller/motor on leading edge of the wing	Unsafe
	Propeller/motor on trailing edge of the wing	Balancing issues while on ground, disturbed air flow, motor cooling issues, limited placement due to ailerons, possible boundary layer ingestion improving cruise flight performance.
	EDFs on leading edge of the wing	Undisturbed airflow, possible utilization of Coanda effect, increased pressure on upper wing surface, improved STOL and stall speed performance, easy installation
	EDFs on trailing edge of the wing	Limited placement due to ailerons, possible boundary layer ingestion improving cruise flight performance, more difficult installation.

Based on the above reasoning, preferred configuration is tractor one utilizing multiple EDFs mounted on the top of the leading edge of the wings due to the following advantages: fully enclosed fans are safe, utilization of Coanda effect – increased upper wing pressure, easy installation, does not obstruct pilot’s view.

3.2.2. DEP Configuration – Size and Quantity of Propulsors

As established in the previous section EDFs are the preferred propulsor type for ultralight aircraft usage. Selection of commercially available EDFs presented in Table 7. EDFs of lower than 120mm diameter not considered as they provide relatively low static thrust.

Table 7. Commercially available EDFs [41-42]

EDF	Inside diameter	Static thrust (median)	Weight	Efficiency	Min QTY	Price	Total price
Schuebeler DS-130-DIA HST	152mm	155N	1.75kg	76-74%	6	3139.00 EUR	18834.00 EUR
Schuebeler DS-215-DIA HST	195mm	232.5N	3.4kg	78%	4	4499.00 EUR	17996.00 EUR
VasyFan VF-160mm Nacelle	160mm	160N	2.5kg	80%	6	2690.00 EUR	16140.00 EUR
VasyFan VF-174mm Nacelle	174mm	230N	3kg	82%	4	3190.00 EUR	12760.00 EUR
VasyFan VF-250mm Nacelle	250mm	450N	10kg	80%	2-3	6100.00 EUR	12200.00 EUR (2 EDFs)

Method of determining optimal number of propulsors proposed by researchers [11] and mentioned in previous sections is presented below:

$$N_{opt} \approx 16.63\phi^{1.38} M_{+}^{0.29}, \quad (1)$$

where: N_{opt} is the optimal number of propulsors; ϕ specific coverage of the wingspan; M_{+} is the specific aircraft mass (eqn. 2).

$$M_{+} = M\frac{g}{\rho}\left(\frac{g}{aI_b}\right)^2 , \quad (2)$$

where: M is aircraft mass; g is specific gravitational constant; ρ is air density; a speed of sound; I_b is mass specific motor torque.

If we consider M = 250kg (MTOW per Table 6), g = 9.81 m/s^2 , ρ = 1.225 kg/m^3 (air density at ground level due to low cruise altitude of proposed aircraft), a = 343 m/s, I_b = 10 m^2/s^2 (used by researchers [11]), ϕ = 0.8 (assumed relative portion of the wingspan that is covered by any number of engines), from eqn. 1 and 2 we get $N_{opt} \approx 3.71$.

Furthermore, review of Table 7 of commercially available EDFs shows that four propulsors is the rational configuration, hence four VasyFan VF-174mm EDFs (Table 8.) selected for the subsequent analysis (Fig. 20).

Table 8. VasyFan VF-174mm Nacelle parameters.

Max. RPM range	Max. Motor diameter	Internal diameter of the cylinder	Max. Discharge speed range
32,000 RPM	64mm	173mm	127 m/s

Nacelles of selected EDFs will be modified (trimmed) to direct airflow on to the upper surface of the wing and to increase the area of effect similar to JabirWatt design (Fig. 22).

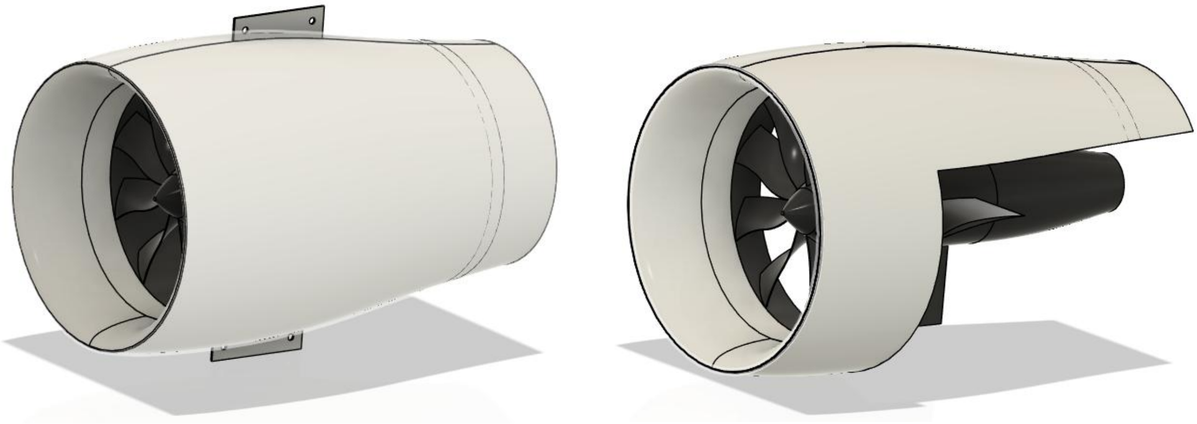


Fig. 20. EDF unmodified nacelle left, modified nacelle right

3.2.3. DEP Configuration – Propulsor Installation

Preliminary airflow simulation (Fig. 21, 22) through modified EDFs (3D CAD model of the selected EDF was provided by the manufacturer) was carried out with Ansys Fluent to determine the required placement on the wing.

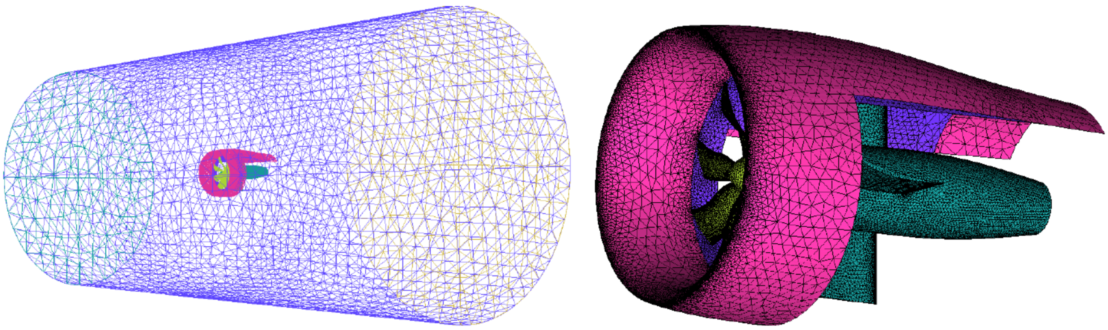


Fig. 21. Simulation meshing

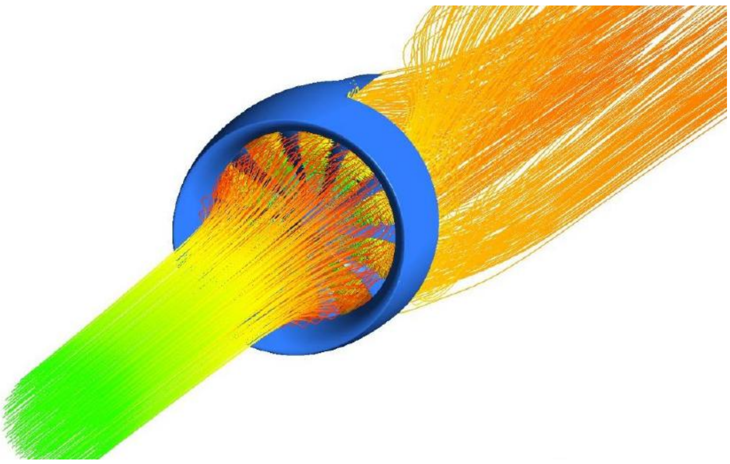


Fig. 22. Simulated airflow

EDF position on the wing adjusted to direct main portion of the airflow onto the upper surface of the wing (Fig. 23).

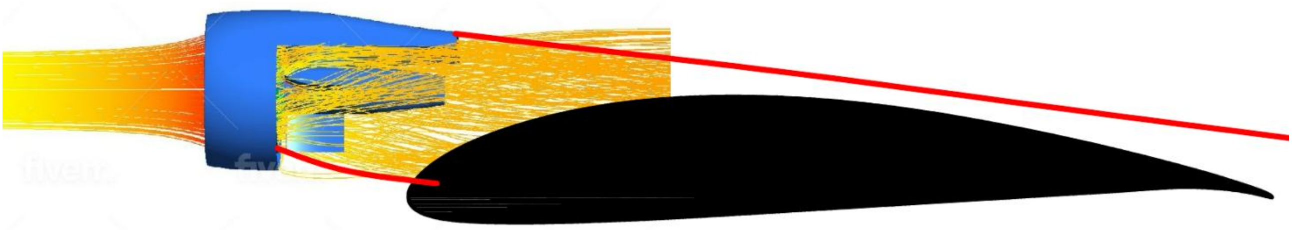


Fig. 23. Powered wing

Notably, simulation demonstrated portion of the airflow directed away from the wing surface, further research would be prudent to find the optimal nacelle geometry to reduce or remove the useless airflow. Principal power control schematic of the ultralight with DEP presented in Fig. 24.

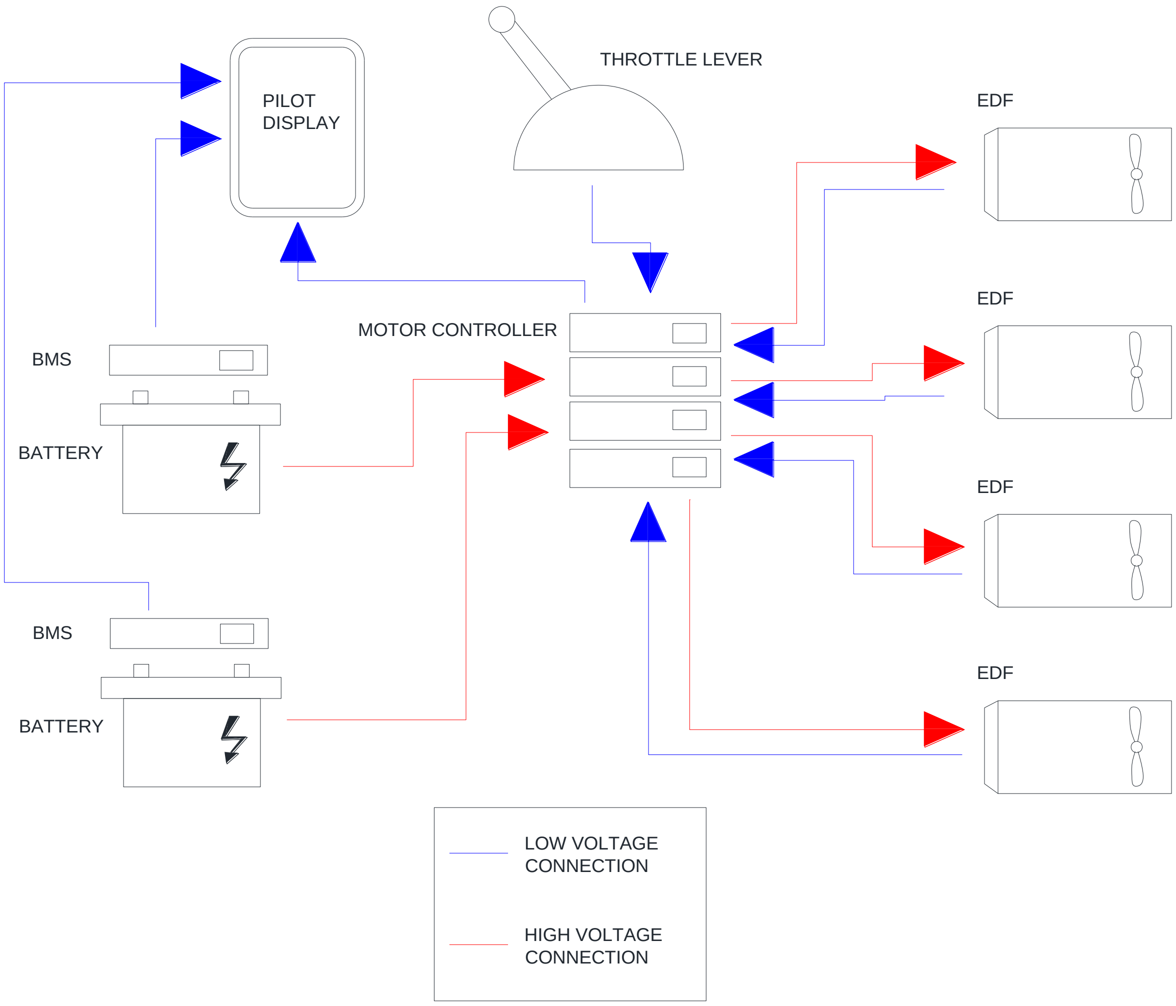


Fig. 24. Principal power control

Main objectives for EDF installation is to maximize the aerodynamical potential, but also to reduce the design, construction and future maintenance efforts. Preliminary EDF mounting structure designed to demonstrate feasibility of the installation on an existing wing design (Fig. 25, 26).

Main spar of the wing is the main longitudinal structural component of the wing in the intended design. It is a sandwich construction with hard foam as core and glass cloth as facing skins bonded together with epoxy adhesive.

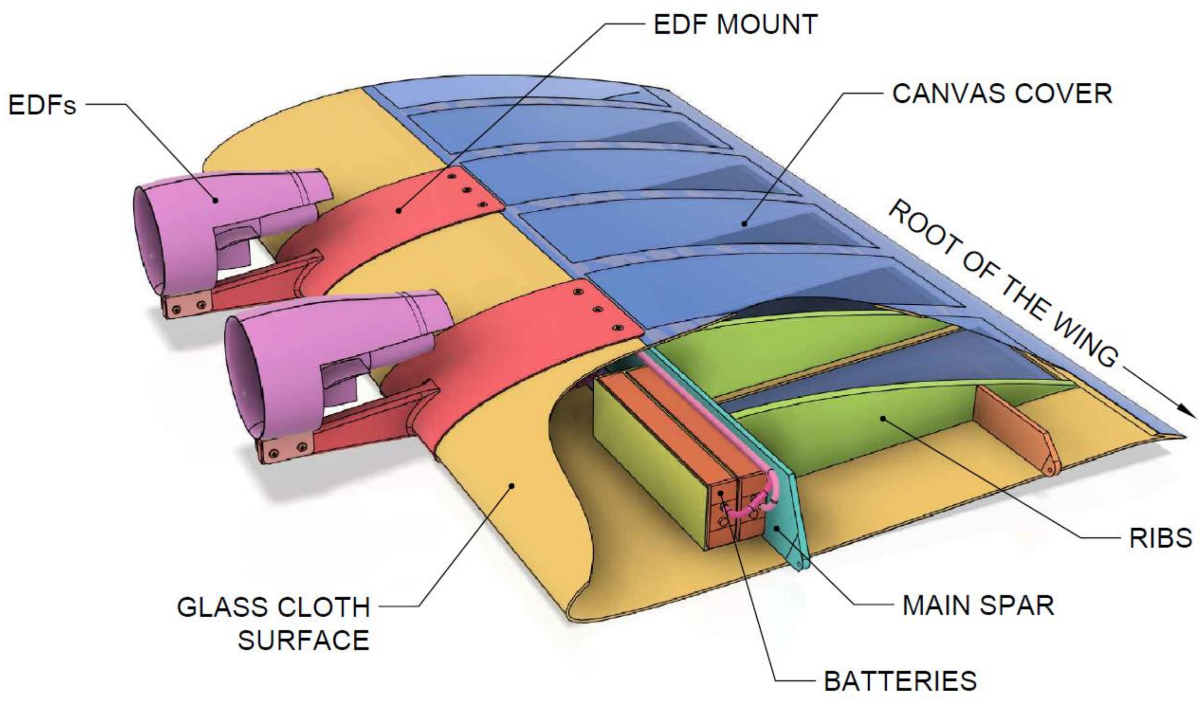


Fig. 25. Preliminary EDF installation

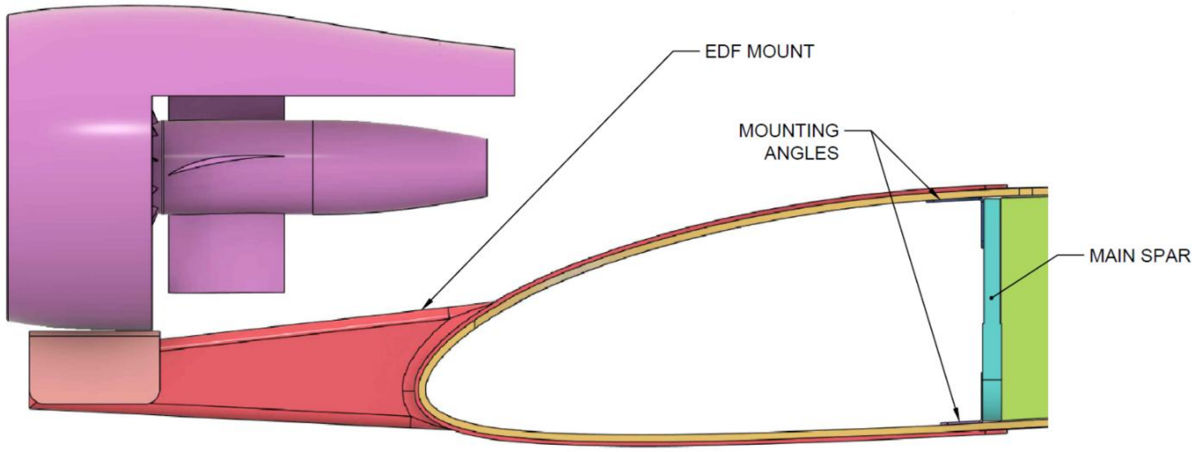
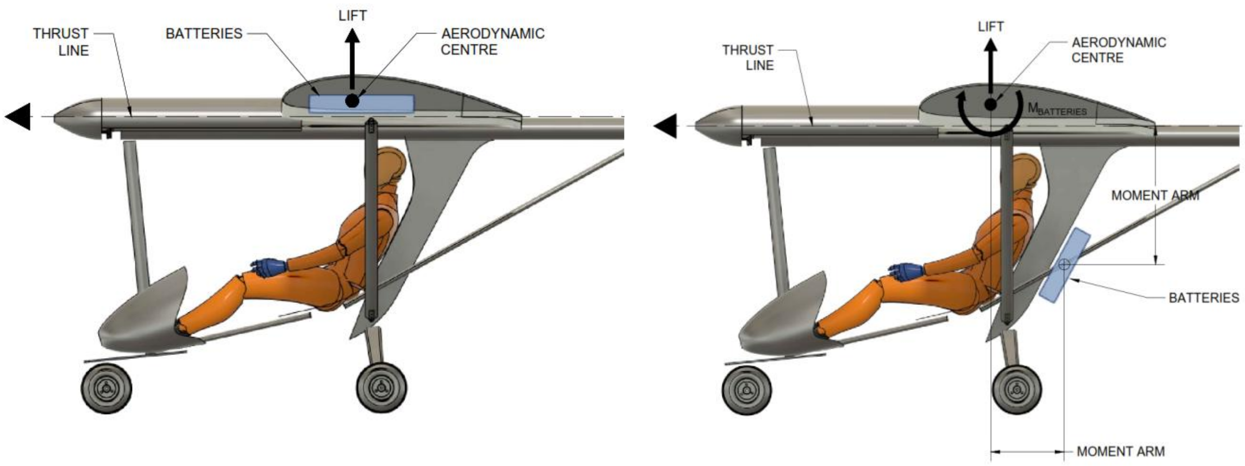


Fig. 26. Preliminary EDF mounting scheme

This allow the main spar to be light but still have a possibility of local structural/stiff elements to be moulded in. The design proposes such local inserts to be installed and folded sheet metal angles mounted on to them to provide anchor points for EDF mounts. Batteries are also installed to the main spar of the wing towards the root of the wing. This provides substantial benefits, briefly discussed in previous sections, of decreasing the wing loading when under lift force, increasing the wing stability, improving the weight and balance of the aircraft and avoiding unwanted moments (Fig. 27).

Having considerable weight of batteries on the thrust line and lift point removes vertical and horizontal moments compared to conventional battery/gas tank location (behind the pilot) which mitigates the necessity of adjusting trim during flight. Such placement also reduces the distance between batteries and EDFs reducing the length of power wires, while the access to batteries remains easy due to wings being designed to be easily removed for storage and transportation.



(a) (b)

Fig. 27. Battery location (a) wing (b) behind pilot

Final investigated ultralight aircraft configuration with distributed propulsion composed for analysis is displayed in Figures 28 and 29.

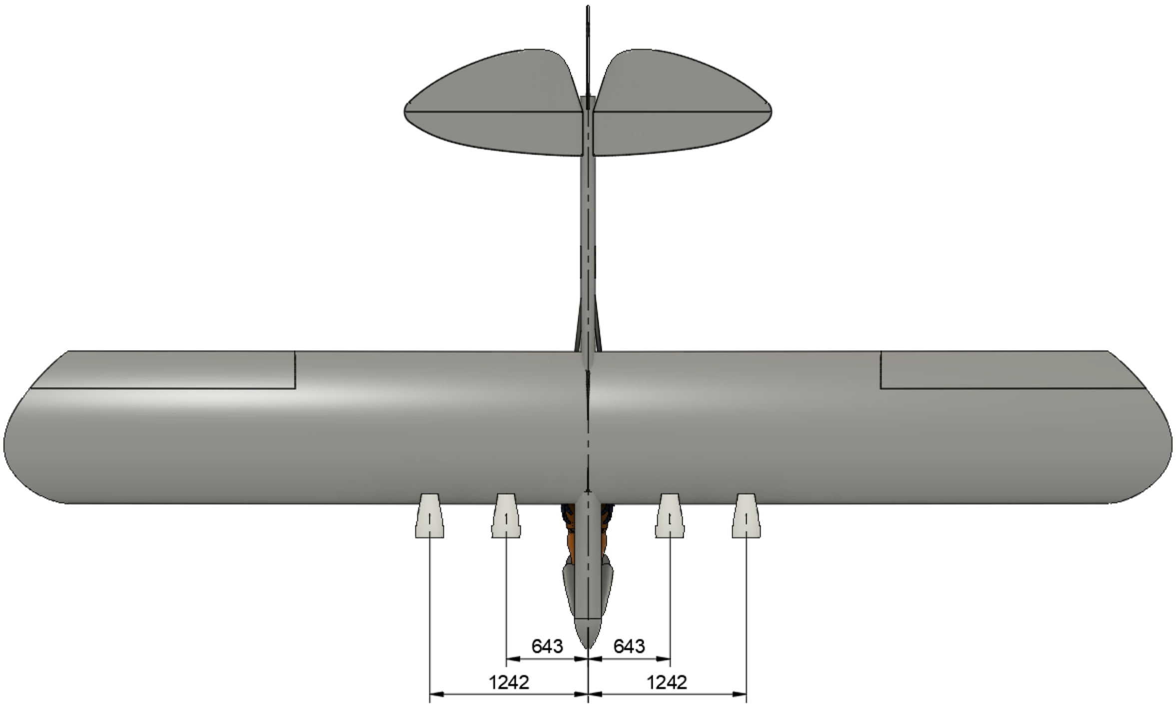


Fig. 28. EDF locations (dimensions in mm)

3.3. Simulation

Simulation will be carried out with ANSYS Fluent software using two equations k-omega Shear Stress Transport (SST) model same as research analysing multiple propeller configuration [30]. Only relevant area (wings and propulsors) are modelled with the main purpose of investigating wing pressure and lift/drag differences between conventional propeller and EDF configurations at cruise flight conditions provided in Table. 4 with Angle of Attack being 0.

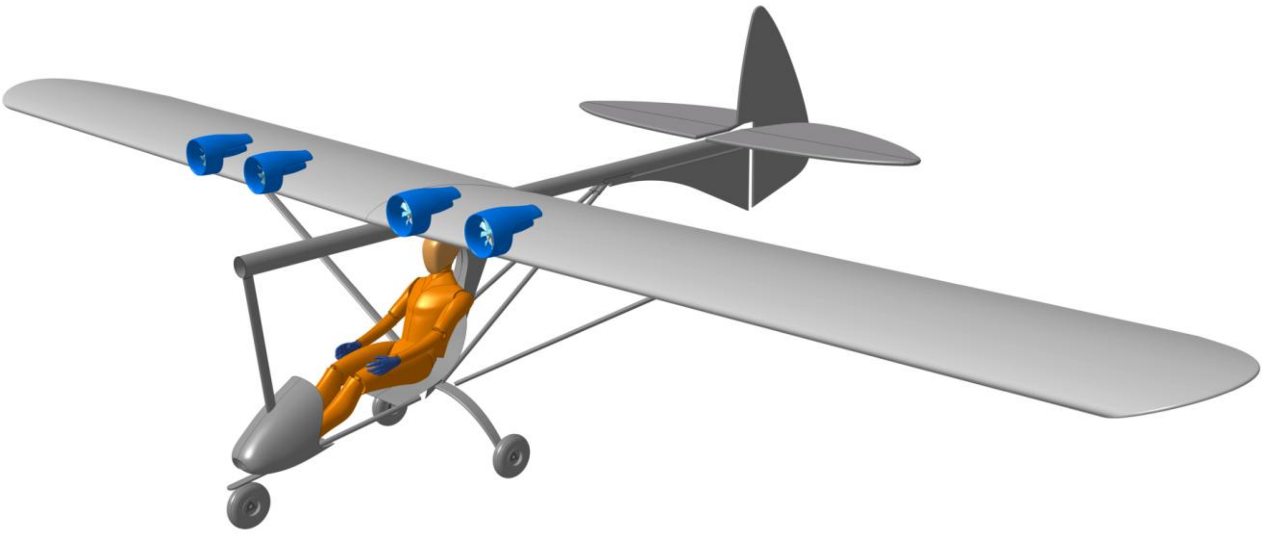


Fig. 29. Overall EDF configuration

Simulation domain of 10m (W) x 5.5m (H) x 17m (L) is used (Fig. 30) with the model placed in the forward section of the domain.

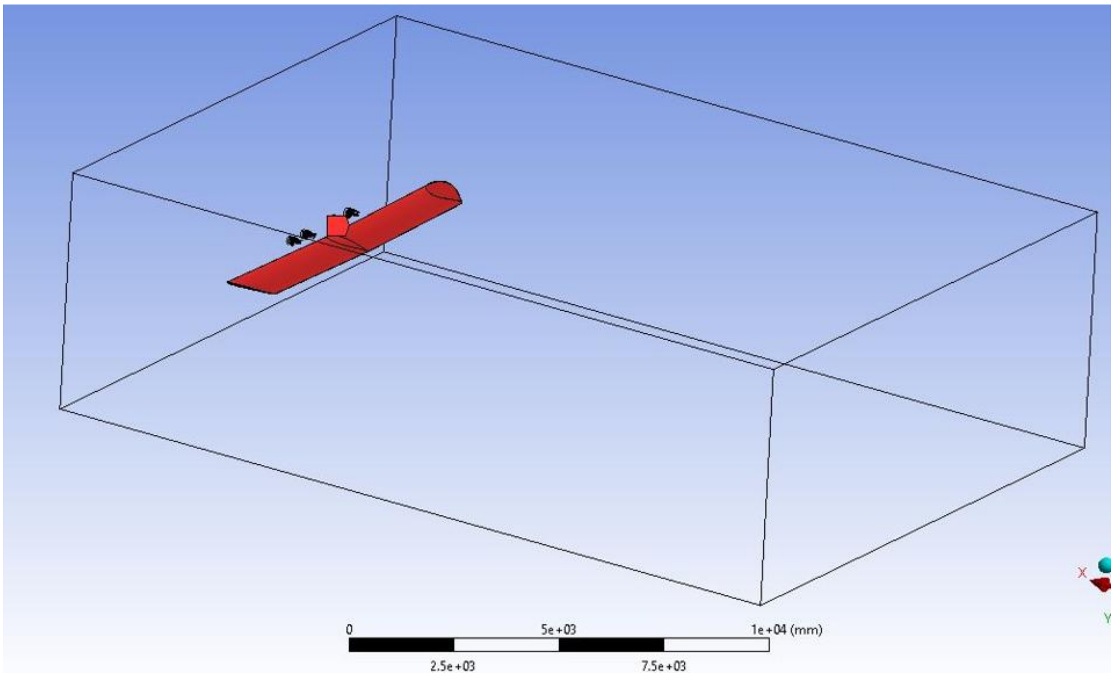


Fig. 30. Simulation domain

Mesh size of 0.5mm was used for boundary areas, mesh size of max 150mm was used outside of boundary areas (Fig. 31 and 32).

3.3.1. Simulation Results – Propeller Configuration

Simulation of propeller configuration showed expected results of generally even negative pressure distribution on the top of the wing (Fig. 33 and 35). Slight unevenness of pressure noticed on top of wing at the root of propeller column, however this is not uncommon due to local induced drag and obstruction of airflow of the propeller mounting itself.

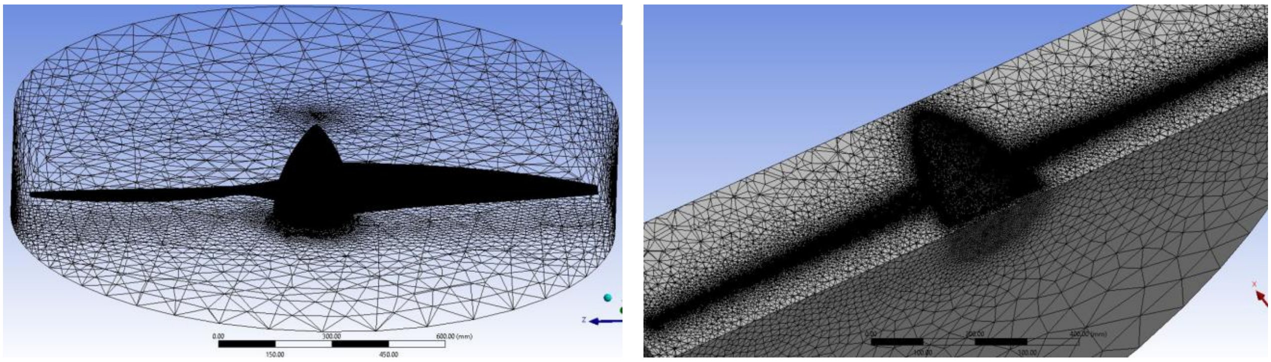


Fig. 31. Propeller mesh.

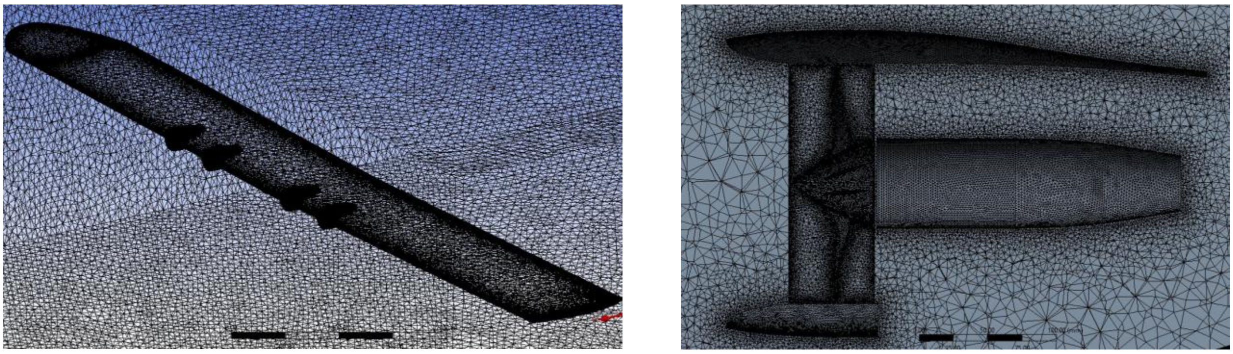


Fig. 32. Wing and EDF mesh

General pressure of -2.000e+02 to -1.785e+02 Pa noticed at wing root area. Bottom wing pressure also displayed expected results (Fig. 34 and 35) – general positive pressure ranging from 1.477e+01 to 7.919e+01 Pa. Expected high pressure line on the leading edge of the wings was also displayed.

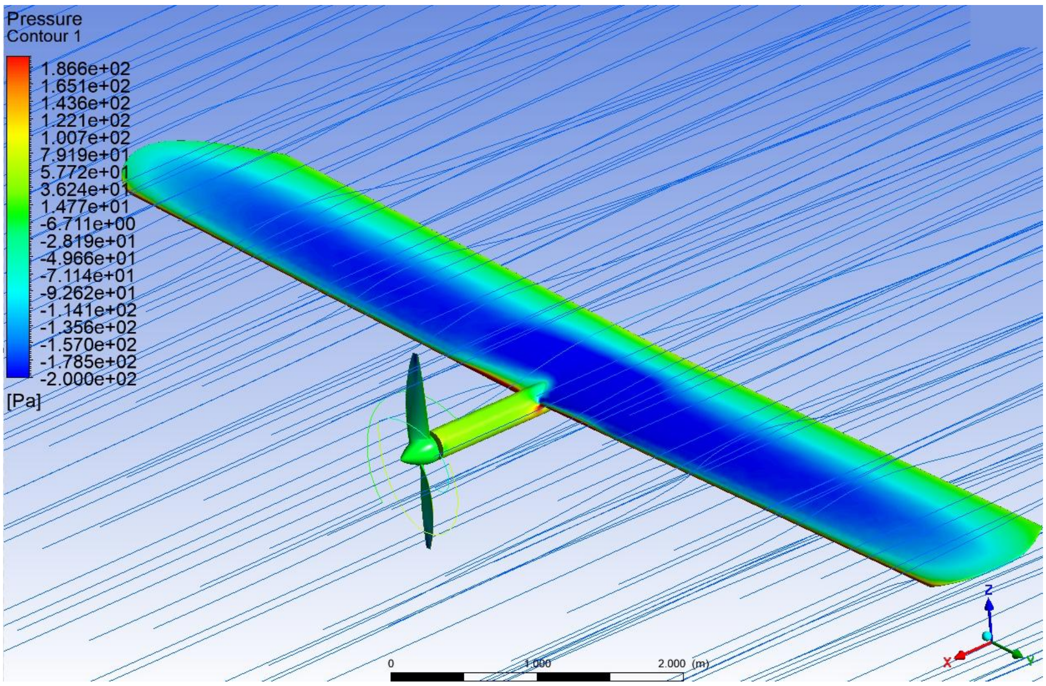


Fig. 33. Pressure distribution – propeller configuration (top of the wing)

Air velocity also showed expected results with propeller providing even thrust at it’s cylinder of operation (Fig. 36). Propeller provided 300.86 N of dynamic thrust with torque of 36 Nm.

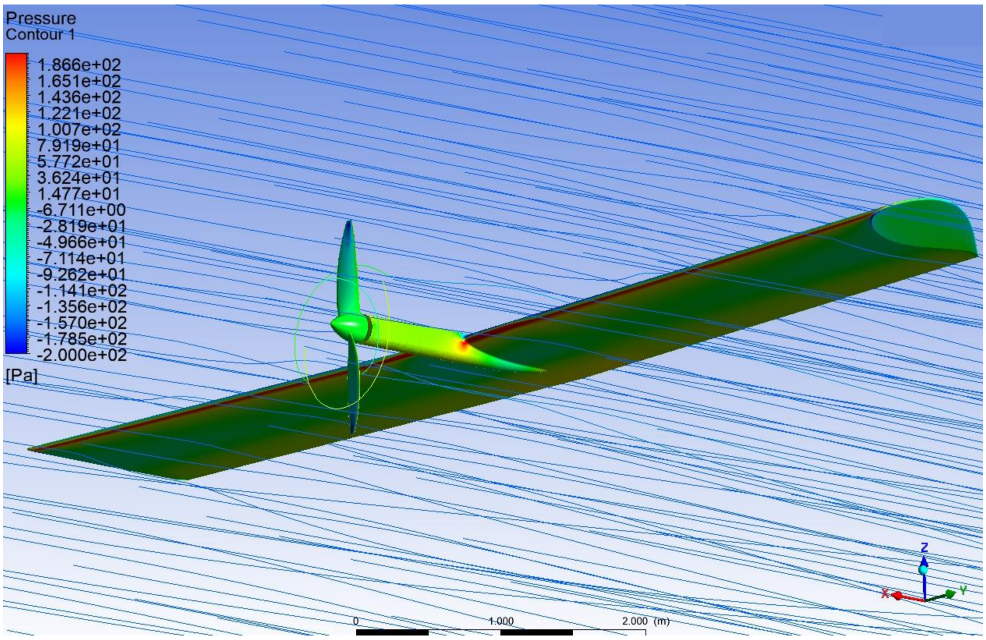


Fig. 34. Pressure distribution – propeller configuration (bottom of the wing)

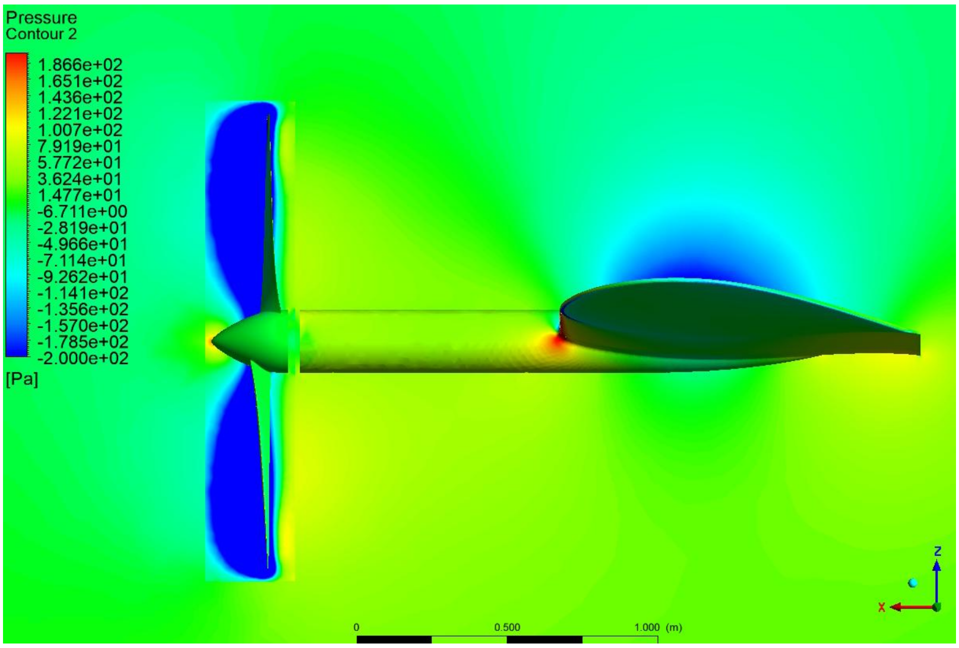


Fig. 35. Pressure distribution – propeller configuration (airfoil)

Overall propeller configuration simulation showed expected results of pressure distribution – negative pressure gradient on top of the wing and positive pressure gradient on bottom of the wing with high pressure line at the leading edge of the wing. Simulation resulted in 1428.87 N of lift force and 65.99N of darg force with propeller configuration.

3.3.2. Simulation Results – EDF DEP Configuration, Initial Analysis

Simulation of EDF configuration showed local areas of high negative but also positive pressure (Fig. 37). Local negative pressure areas reached up to -1.000e+03 Pa. Unexpected positive pressure areas reached up to 9.329e+02 Pa

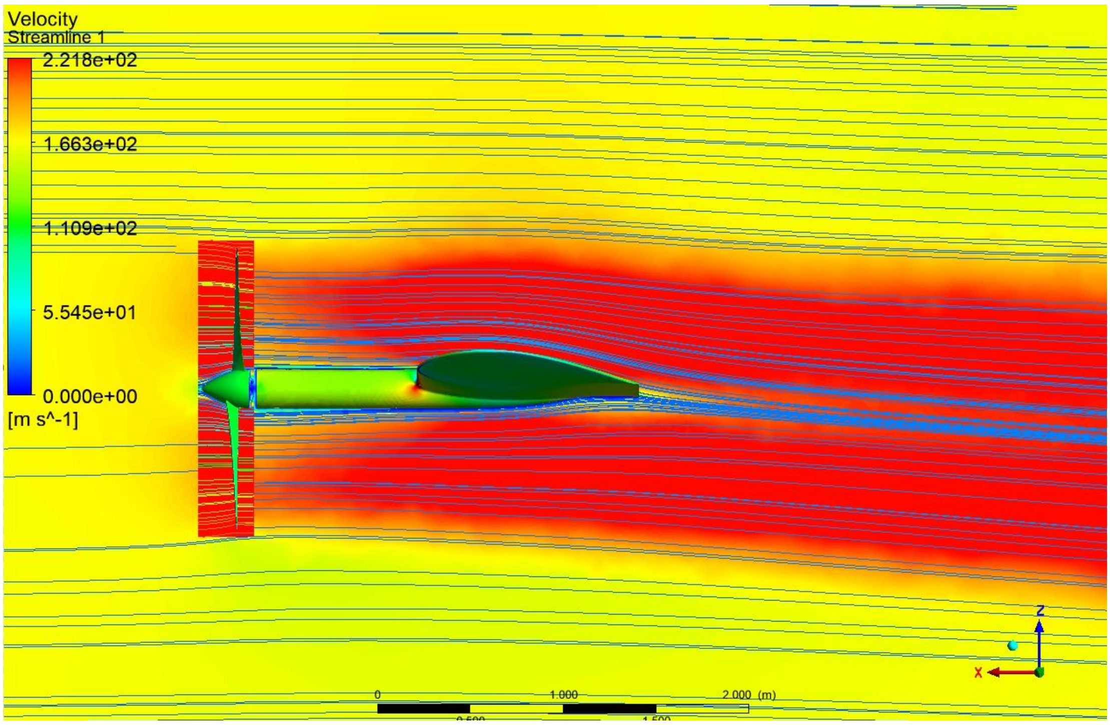


Fig. 36. Velocity – propeller configuration (airfoil)

Overall, airflow from modified nacelles was displayed to be very turbulent, possible reason for high pressure areas is the loss of diffuser function of the nacelles once they were modified.

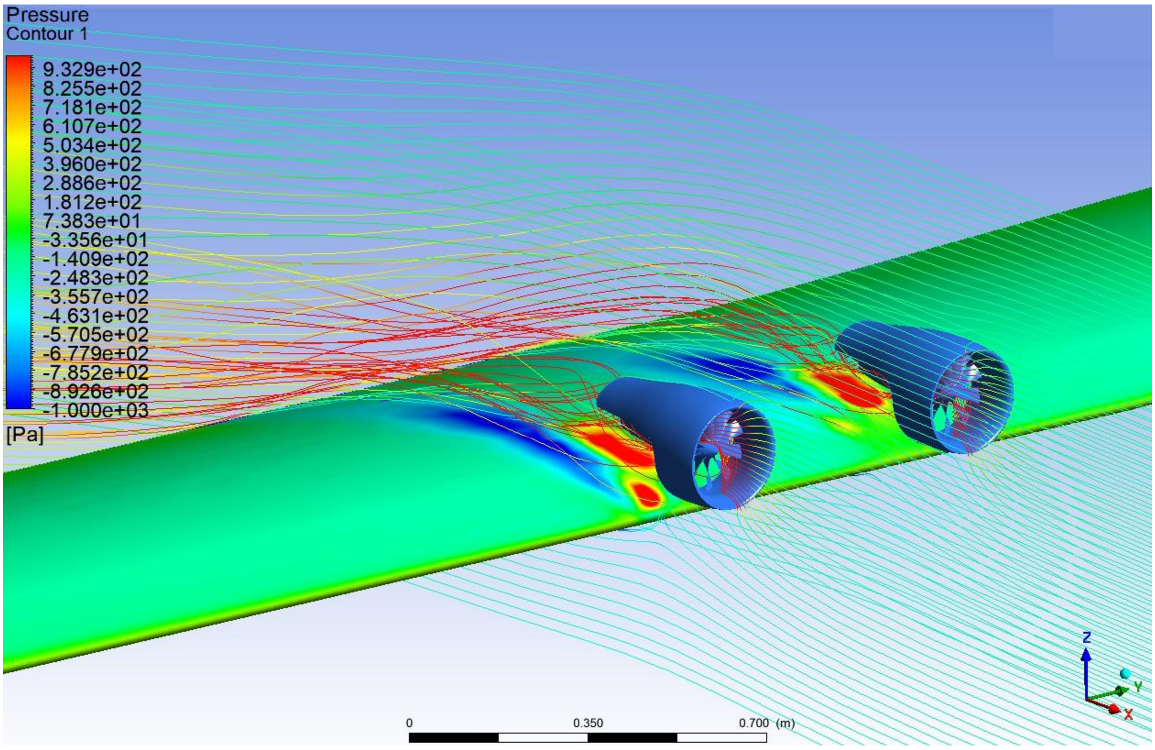


Fig. 37. Pressure distribution – EDF configuration (isometric)

This can be more clearly seen on the side view of the pressure simulation (Fig. 38). Inside upper wall of the nacelle has a high pressure area, but since the lower part of the nacelle is trimmed, high pressure is transferred to the wing upper surface.

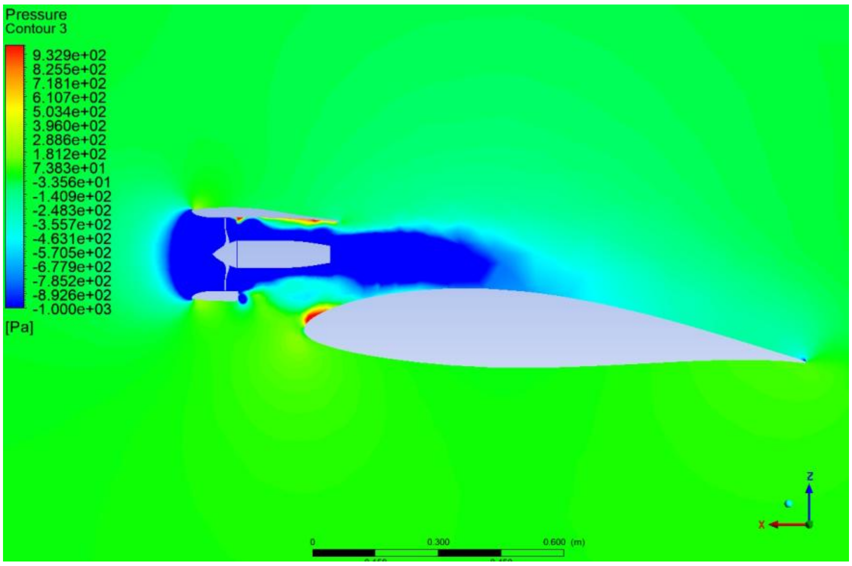


Fig. 38. Pressure distribution – EDF configuration (airfoil)

Velocity contour showed somewhat expected results (Fig. 39) with the flow being delivered to upper surface of the wing. However, some turbulent flow noticed towards upper side, again, possibly due to nacelle modification.

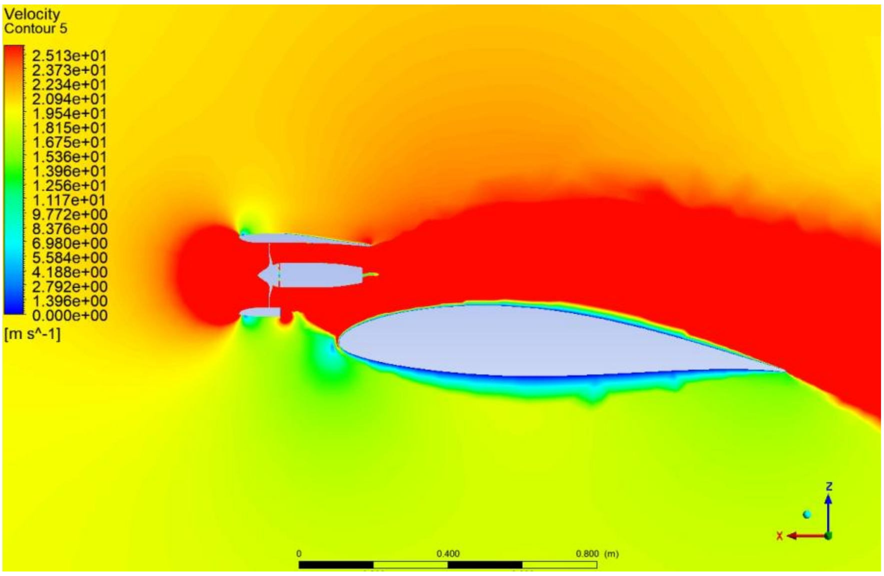


Fig. 39. Velocity distribution – EDF configuration (airfoil)

Results also showed that each EDF provided unexpectedly low 51.01 N mean dynamic thrust. Manufacturer's specification defines the subject EDF being at a range of 230 N of static thrust and while there's an expected degradation of thrust from static to dynamic conditions, displayed difference is unexpectedly high. It is assumed that the unreasonably large disparity of static and dynamic thrust was due to the manufacturer provided 3D CAD model not being accurate.

Overall, initial EDF configuration analysis showed expected local high negative pressure areas, but also unexpected local high positive pressure areas adjacent to EDF installation. Also the air flow showed to be somewhat more turbulent than expected, possibly due to trimmed nacelles. Furthermore, simulation showed very high disparity between advertised static thrust and resultant dynamic thrust of the EDFs. Initial EDF simulation showed 1616.5 N lift force, 95.23 N drag force and total 204.04 N of total thrust.

3.3.3. Simulation Results – EDF DEP Configuration, Optimized Analysis

EDF model fan was reworked to reach similar static thrust as advertised by the manufacturer (Fig. 40).

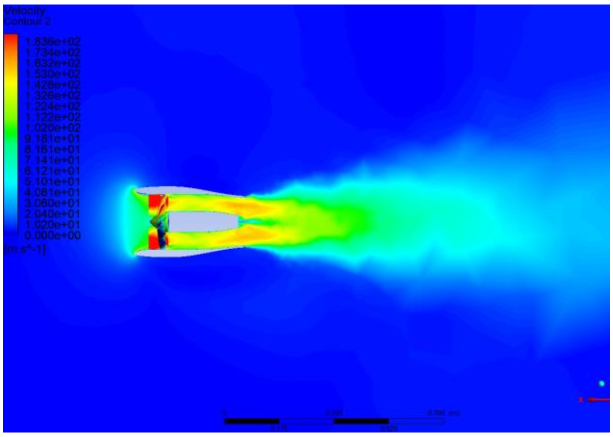


Fig. 40. Reworked EDF

Reworked EDF was able to reach 226.52 N static thrust under simulation (2.5% difference to advertised by the manufacturer). Wing with reworked EDF, but with full nacelles, was simulated in flight conditions (Fig. 41, 42).

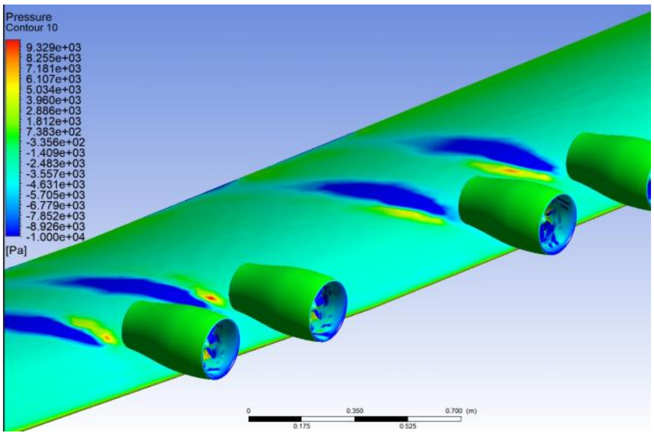


Fig. 41. Pressure distribution – reworked EDF configuration (isometric)

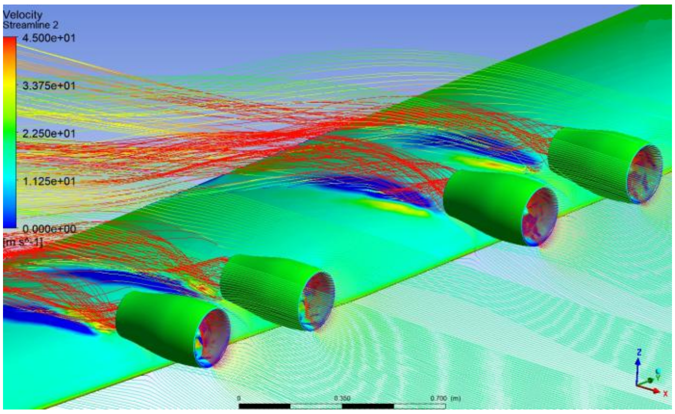


Fig. 42. Pressure distribution/streamlines – reworked EDF configuration (isometric)

Simulation showed local high negative pressure areas, but with minimum positive pressure areas. Negative pressure areas reached higher values (max -1.000e+04 Pa) compared to initial EDF analysis. Additionally, the airflow was less turbulent and more evenly distributed across the wing surface. Velocity contour showed less turbulent flow compared to initial EDF analysis, the flow was more streamlined and more attached to the upper wing surface (Fig. 43).

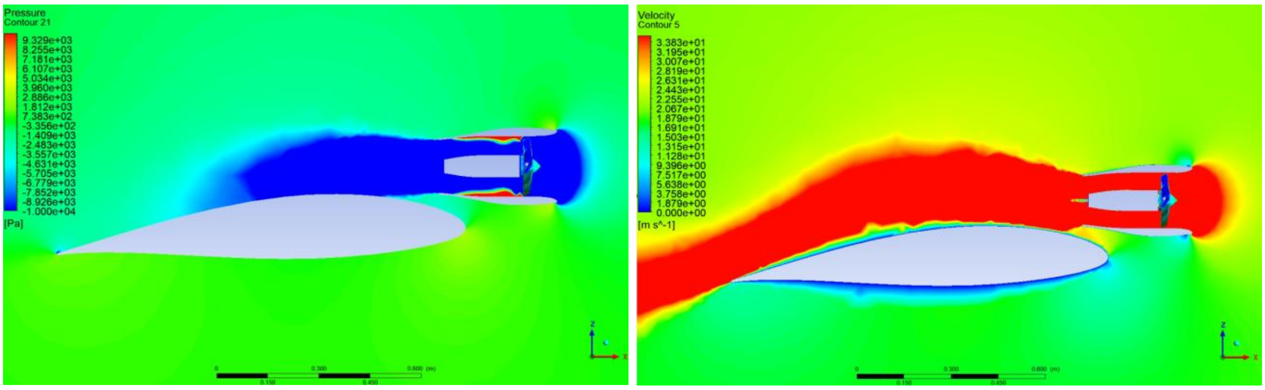


Fig. 43. Pressure distribution (left) and velocity (right) – reworked EDF configuration (airfoil)

Overall, optimized EDF analysis showed significantly better results compared to initial analysis, 2215.39 N of lift force was generated, even tough slightly higher drag force of 115.16 N was displayed. Also, no unexpected high positive pressure areas were noticed and airflow was much less turbulent, hence producing better results.

3.3.4. Simulation Results – EDF DEP Configuration, Optimized Analysis, Modified Nacelles

Final simulation was carried out with EDFs with reworked fans and trimmed nacelles to more accurately investigate the initial assumptions of nacelle modification benefits. However, simulation displayed the unwanted local high positive pressure areas similar to initial analysis (Fig. 44).

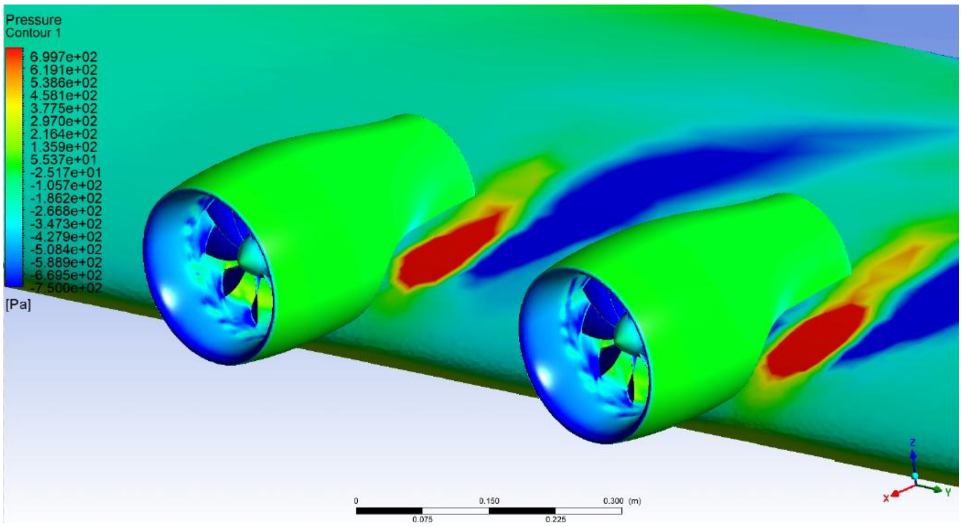


Fig. 44. Pressure distribution – reworked EDF – modified nacelle configuration (isometric)

Additionally, turbulent flow was observed (Fig. 45) resulting in suboptimal aerodynamical characteristics.

Overall simulation resulted in 2125.76 N of lift force, 133.27 N of drag force, total of 489.25 N thrust, with single EDF having mean thrust of 122.31 N.

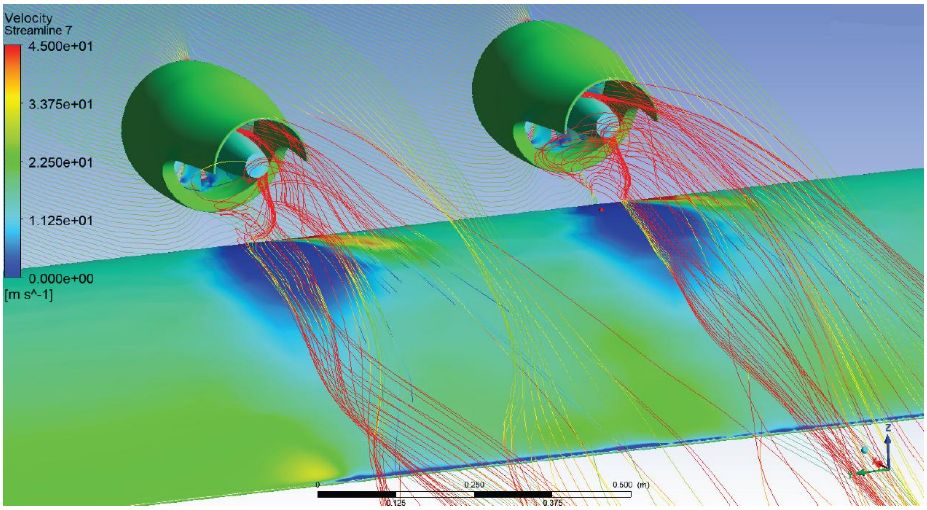


Fig. 45. Pressure distribution – reworked EDF – modified nacelle configuration (isometric)

3.4. Simulation Results – Summary and Considerations

Summary of the main resultant parameters of the simulation provided in Table 9.

Table 9. Lift and drag forces of simulated configurations.

Configuration	Lift force, N	Drag force, N	Dynamic Thrust, N (total)
Baseline configuration – single propeller	1428.87	65.99	300.86
EDF configuration – manufacturer provided model, modified nacelles	1616.50	95.23	204.04
EDF configuration – optimized model, unmodified nacelles	2215.39	115.16	546.17
EDF configuration – optimized model, modified nacelles	2125.76	133.27	489.25

Results show that single propeller configuration had the lowest drag and lowest lift force in the simulated conditions. EDF configuration with manufacturers provided model showed lower than expected dynamic thrust, but produced a lift force which was higher than the baseline configuration. Best results were for EDF configuration (optimized model) with unmodified nacelles – highest lift and thrust values displayed. Initial assumptions that modified nacelles would have a higher lift due to affected greater area of the wings were not confirmed. Even though the results shown a slightly greated negative pressure area compared to unmodified nacelles, it also introduced larger area of positive pressure (Fig. 42). Most probable reason for larger positive pressure area is due to reduction of difuser function of the nacelle. Further analysis is recomended to investigate optimal nozzle geometry to further improve the lift, especially closed high aspect ratio exit nozzles previously investigated by researchers [38] and briefly mentioned in Section 2 of this work. Additionally, physical wind tunnel testing will be required when the design is optimized and matured, however presented CFD simulations are inline with other researchers work [30] in terms of software, parameters, modelling and meshing, hence can be used as a proof of concept and to derive initial conclusions.

Power consumption also needs to be addressed, EDF VF-174 Nacelle max power is 18kW, assumed continuous power 14.4kW (80% of max power), running all four engines this power level with 10.4 kWh battery capacity (same as Aerolite EV-103 per Table 4.) would have an estimated preliminary run time of approx. 11min, which is a low endurance value. However, it is visible (Fig. 44) that even with a low total thrust of EDF configuration (manufacturer provided model, modified nacelles), it is able to produce higher lift compared to single propeller configuration, hence the EDF configuration might provide similar or even lesser power consumption while maintaining required lift.

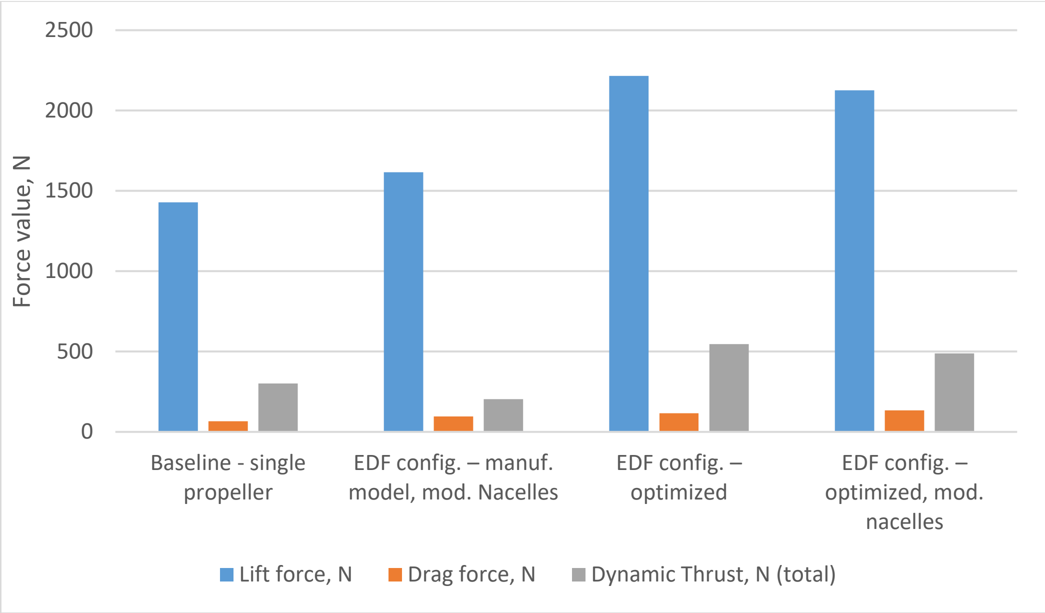


Fig. 46. Lift, drag and thrust chart

Furthermore, additional benefits of short take-off and landing, reduced stall speed, not impaired visibility in flight, no emissions, cheaper operation and easier maintenance makes DEP with EDFs a viable configuration for ultralight aircraft.

3.5. Chapter summary

Simulations showed that even when providing lower total thrust than propeller, multiple EDFs positioned on the upper leading edge of the wing can produce higher lift. However, it was noticed that open exit nozzle EDFs produce unwanted positive pressure areas on the upper wing surface as well as uneven, turbulent flow. Closed exit nozzle EDFs provide even flow and no unwanted positive pressure areas significantly improving the lift compared to propeller configuration.

4. Economic Considerations

While the business model of light all electric VTOL aircraft such as KittyHawk, Vertical Aerospace VX4, Joby and Lilium (Fig. 5) are not the based on the aircraft itself but rather on the service they will provide (air taxi) [43], ultralight aircraft does not have such capability. Furthermore, all electric ultralight aircraft are not able to utilize any of the economical benefits that are common for land all electric vehicles, such as government benefits (for buying a vehicle), which has a direct impact on EV sales [41] or value adding services (like car sharing) [44]. Other economical benefits of all electric ultralight aircraft must be sought.

4.1. Development

Aircraft life cycle comprises of five main steps: development, manufacturing, assembly, operation, and End-of-Life (EoL) (Fig. 47):

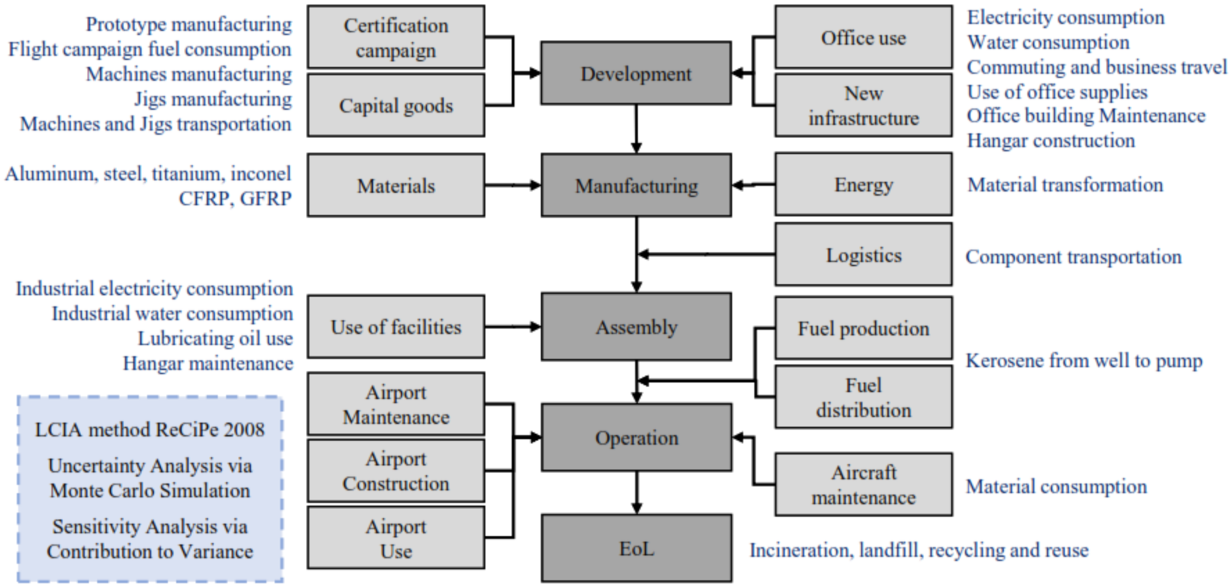


Fig. 47. Aircraft life cycle scheme [45]

Each of the main steps have their own economical considerations for all electric ultralight aircraft. Research and development is one of the areas where government subsidies in the form of grants are extended, examples of such grants are provided below:

- In 2023 Dovetail Electric Aviation receiving a multi-million research grant from Ministry of Australian Ministry of Industry and Science [46].
- In 2019 U.S. Department of Energy's (DOE's) Advanced Research Projects Agency-Energy (ARPA-E) granted $55 million in funding for two programs to support the development of low-cost electric aviation engine technology and powertrain systems [47].
- In 2023 The UK Government has announced that it will provide £113m through the Aerospace Technology Institute (ATI) for UK companies working in electric aircraft development [48].
- In 2023 U.S. Air Force awards Electra.aero strategic funding partnership valued up to $85M to develop full-scale pre-production eSTOL aircraft [49].

– All electric passenger airplane Maeve Aerospace BV has been selected for a financial injection of 17.5 million euros from the European investment fund European Innovation Council (EIC) [50].

Private sector investments also form a substantial part in backing electric aviation. Taking Lilium aircraft as an example, company received more than $350 million in their Series B financing round and another $460 million through Special Purpose Acquisition Company (SPAC) with investors such as BlackRock, Honeywell and Palantir [51]. UK based Vertical Aerospace also had similar success and raised $300 million with their IPO and having strategic investments from Microsoft, American Airlines, Rolls-Royce and others [52]. Ultralight aviation does not have such scalability as intended for Air Taxies such as Lilium or Vertical or passenger aircraft like Maeve. Additionally, in aviation sector government subsidies extend more towards the services/goods providers such as aircraft and component manufacturer's, air traffic control, airports and airlines rather than end user, but it is obvious that there is great interest in investment to electric aviation that even ultralight aircraft could tap into especially considering the increasing trend of sustainability and regulatory push toward clean transport.

4.2. Manufacturing and Assembly

After the development phase, manufacturing and assembly does not substantially differ between conventional and all electric ultralight aircraft, no unproven manufacturing methods or materials are used. Price of the final product is a direct result in components used and one of the main components are batteries which showed a substantial price decrease in the past decade – from 668$/kwh in 2013 to 137$/kwh in 2020 [51]. Researchers investigated the possible price future scenarios for lithium-ion batteries identifying three possible narratives: rapid price stabilization due to insufficient raw material supply, stoppage of decreasing prices but no physical shortage of raw materials, further price decrease due to market disrupting technologies (such as solid-state batteries) [51]. 2023 International Energy Agency publication further reviews the raw material and battery prices in the past decade and showing a substantial price spike in Lithium carbonate in the year 2021-2023 [52] (Fig. 48):

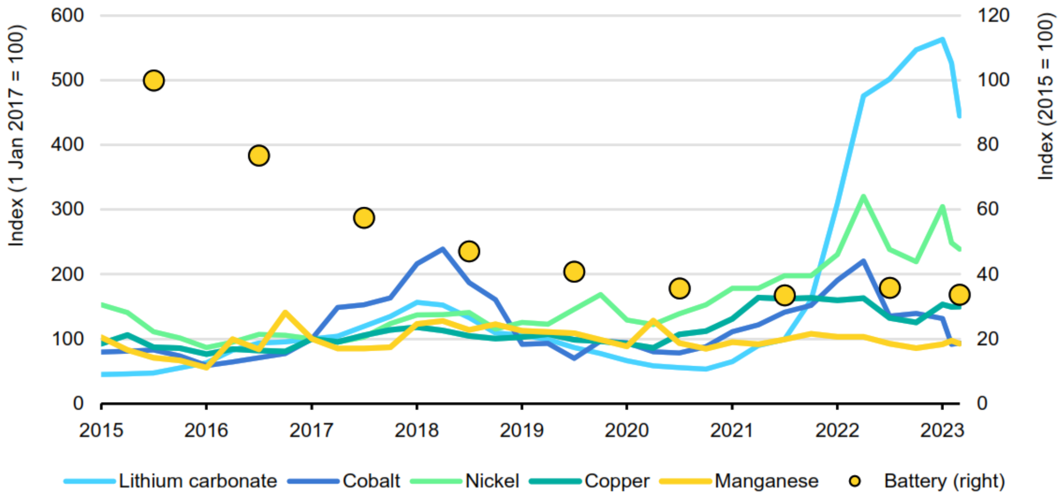


Fig. 48. Price of selected battery materials and lithium-ion batteries, 2015-2023 [52]

Even though the price of the actual batteries did not show a great impact due to spike in Lithium price, it has stabilized hence it is unlikely that batteries would be a cost saving component in future ultralight aircraft assembly with the current technology.

While the market share of the BLDC motors is increasing and will continue to increase due to wider adoption of electric vehicles, the prediction of price trend of the actual motors is scarcely evaluated. Comparing the prices of IC engines (example: popular Polini Thor 250, 36HP) and BLDC motors (15kW continuous power 72v 2000 RPM) does not show a significant difference, however utilizing EDFs is more costly, a set of four EDFs (VasyFan VF-174mm Nacelle) preliminary required to produce enough thrust for ultralight aircraft would cost around 13000 EUR compared to approx. 3000-4000 EUR for standard IC engine or a BLDC motor. While the propeller and accessories prices would have to be added to BLDC motor price for a full propulsion unit, it is still significantly less than the cost of EDF kit. The most common use of commercially available EDFs is for RC models, which mostly utilize 70-80mm diameter models. This in turn affects the price and variety of the offered products. Current low demand for larger diameter EDFs turns manufacturers away from producing more varied and cheaper higher diameter models, but the rise of fully electric manned aviation will incentivize companies to adjust their production towards such models. However, currently, EDF propulsion price is substantially higher than single motor configurations.

4.3. Operation

There are few economic incentives for buyers to choose all electric ultralights compared to the ICE models, one of which is lower operating costs. It is considered that charging costs are lower that fuelling costs for ground vehicles and the same is relevant for aircraft. While the savings value will differ depending on the frequency, type and duration of flights, costs can be further reduced by charging batteries overnight due to lower electricity price. Other incentive is lower maintenance costs. For ground vehicles it is assumed that maintenance costs are approximately 11% lower in total ownership costs (TCO) compared to ICE vehicles. This is due to ICE vehicles having significantly more moving parts in their powertrains compared to EVs. This applies to aircraft as well, entire fuel and oil system is not required. Additionally, optimally designed battery/motor installation can reduce the maintenance costs even further and possibility of less required maintenance. Unconventional ultralights with VTOL capabilities (Jetson One, Blackfly) offer additional incentive of not requiring aerodrome for takeoff, however VTOL capabilities significantly decreases endurance and greatly increases the upfront costs of the aircraft making it a luxury product. Review of the of the prices of existing of conventional configuration all electric single motor/propeller ultralights shows that they don’t differ greatly from ICE variants (around 40000USD) and the main dissimilarity is, again, the greatly reduced endurance. Cost of utilizing DEP and EDFs might further increase the price of an aircraft while not having great improvement on the endurance, even if the actual flight performance is improved (decreased stall speed, shorter takeoff).
Currently one of the greatest economical challenges that ground EVs are facing is the depreciation. EVs are depreciating appreciably faster than ICE vehicles due to rapid advances in battery technology. This is due to ground EVs having the battery system integrated to their mainframe, which is not easily accessed. Proposed ultralight aircraft design have easily accessed and replaced batteries eliminating the “fall-behind” disadvantage.

Summarizing the economical impact of DEP ultralight aircraft some advantages that can be expected compared to ICE variants, such as investment for development and cheaper operational and maintenance costs. However, components required for DEP are currently more expensive, making the up-front cost of the aircraft higher. Buyers would need to be focused on improved flight characteristics, environmental impact, and cheaper operation to be swayed from lower ICE ultralight aircraft costs. Lastly, aircraft EoL not further discussed in this section as no obvious advantages or disadvantages are seen for DEP ultralights compared to ICE ones.

4.4. Chapter Summary

Ultralight aircraft with DEP would be more expensive compared to single propeller/motor configurations due to price of propulsion system – approximately 9000 EUR more for four EDFs compared to single engine/motor. However, it is expected that the ownership costs would be 11% less, similar to land electric vehicles, due to lower operating costs (gas versus charging) and lower maintenance costs. Additionally, it is feasible to receive investment for design and manufacturing phase of DEP ultralight aircraft due to current major commercial interest in electric aviation.

Conclusions

1. Distributed electric propulsion is a contemporary research field which is only now being put in practice mostly in eVTOLs such as VX4 and Joby. DEP improves aerodynamic characteristics, depending on configuration, by increasing dynamic pressure on the upper surface of the wing or by boundary layer ingestion. Electric ultralight aircraft do not currently utilize DEP, but rather conventional single propeller configurations. These designs are almost identical to ICE variants only using electric motors and replacing gas tanks with batteries. Few single seat aircraft designs emerged utilizing multiple electric engines for propulsion, such as Jetson One and BlackFly but these do not strictly fall into ultralight category, are expensive and suffer from endurance problems. For ultralight use, it's preferred to due without fly-by-wire and PCA systems as these increase price and weight, and utilize conventional mechanical control systems. Only required systems are electric throttle control and battery management systems
2. Aerodynamic simulations showed that multiple EDFs positioned on the leading edge of the wing results in slight drag force increase but also substantial increase in lift force compared to single propeller configuration. Simulated baseline propeller configuration generated 1428.87 N of lift force with 300.86 N of thrust, while EDF configuration generated maximum of 2215.39 N of lift force with 546,17 N of thrust. Significantly, results showed that even DEP configuration with lower dynamic thrust than propeller – 204.04 N, was able to generate higher lift force – 1616.50 N indicating that DEP is a feasible alternative to conventional propulsion system. However, initial assumptions that modified (trimmed) EDF nacelles would provide greater lift due to larger area of effect were not proven, further research is prudent to optimize the exit nozzle geometry, especially looking at closed high aspect ratio exit nozzles to maximize the potential lift.
3. Ultralight aircraft with DEP are not able to utilize the economical model of air taxies as heavier aircraft with DEP and would not be subject to government benefits common for land electric vehicles. However, due to general trend of governmental and private investment in electric aviation, it is feasible that some investment for all electric ultralight aircraft design and production is possible. Compared to ICE ultralights, or even electric ultralights with conventional design, the DEP variant would be more expensive due to higher cost of multiple EDFs (approx. 13000 EUR for four EDFs, compared to approx. 3500 EUR for standard IC engine or a BLDC motor). This is due to higher diameter EDFs being a niche product and having a high price compared to commonly adopted ICE or even electric motors. It is expected that such EDFs would see a reduction in price gradually due to widening adoption and mass production bringing the entire ultralight aircraft price down. Largest economical benefits of all electric ultralight are cheaper operation (gas vs charging) and easier maintenance, while not having a detrimental depreciation issue, common to all electric land vehicles, due to batteries being easy to replace.

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