

Aerodynamic Enhancements due to the Use of Distributed Electric Propulsion

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Abstract — *To reduce the carbon emissions and noise produced by airplanes, aircraft manufacturers are looking at new technologies to comply with regulations and to improve performance. One alternative is using DEP (Distributed Electric Propulsion), which significantly enhances aircraft performance by coupling propulsion and air dynamics by distributing adequately designed propellers along a lifting surface. The benefit of this system is that electric motor and energy storage technologies have improved in power-to-weight ratio and increased in electric engine efficiencies and battery density over the past 30 years, resulting in an extremely quiet system and zero vehicle emissions. This study aims to produce a valid method to predict the effects of utilizing CFD (Computational Fluid Dynamics) on the design of DEP in aircraft to design a more efficient and improved aircraft performance by analyzing two geometries, one with DEP with the propellers modelled as actuator disks, and the other without DEP, using steady CFD. The exploration and examination of DEP will change the aerodynamics of an aircraft by knowing how they respond to lift and drag, which are vital factors when flying.*

Keywords — *Angle of Attack (AOA), Distributed Electric Propulsion (DEP), Drag Coefficient (C_D), Lift Coefficient (C_L).*

INTRODUCTION

There are many propulsion systems, and one of them is distributed propulsion. Distributed Propulsion (DP) has been around since early aviation. DP has a specific approach for delivering the aircraft with the required energy to power multiple, hence distributed, propulsive devices via an electric transmission system. DP is a system where an array of propulsor engines along the

aircraft produces the thrust [1]. One type of DP is Distributed Electric Propulsion (DEP). When considering the multiple electric motor-driven propulsors of a Distributed Electric Propulsion (DEP) system, the traditional word “engines” related to an aircraft power plant is intentionally not used to avoid confusion between the power sources of the aircraft and the propulsors [1]. The propulsors that produce thrust on the DEP system do not use a mechanical driveshaft or any mechanical power source. Power sources are any combination of electrical power-producing devices (electric generator, fuel cell, etc.) and energy storage devices (battery, capacitor, etc.). At the same time, the propulsors can be any combination of thrust-producing devices, such as electrically driven propellers or fans. DEP aircraft concepts involve using multiple electric propulsors around an airframe with one or more independent electric generators or energy storage devices [1].

To reduce the carbon emissions and noise produced by airplanes, aircraft manufacturers are looking at new technologies to comply with regulations and to improve performance. One alternative is using DEP (Distributed Electric Propulsion), which significantly enhances aircraft performance by coupling propulsion and air dynamics by distributing adequately designed propellers along a lifting surface. The benefit of this system is that electric motor and energy storage technologies have improved in power-to-weight ratio and increased in electric engine efficiencies and battery density over the past 30 years, resulting in an extremely quiet system and zero vehicle emissions. The DEP is a type of powered flight propulsion system where multiple engines are distributed on the wing.

The task is to improve the aerodynamics, that is, the geometry of the aircraft and shape, to help

with fuel efficiency, handling performance, and the takeoff/landing field length.

This project intends to gather all the advantages of electric motor designs, implement them in a small aircraft that flies at low velocities, and compare it to a standard aircraft. The small aircraft will be the one designed by PUPR's SAE Aero-design team (Polytechnic University of Puerto Rico Society of Automotive Engineers Aero-design team) for their 2018 Capstone project, utilizing the airfoil shape General Aviation (Withfield) -2 (GA(W)-2) [2]. The DEP design and the design without DEP will be analyzed to determine their lift, drag, and momentum coefficients. It is expected that the DEP results will serve to produce a valid method to predict the effects of using DEP on aircraft.

Description

It is proposed that the design of PUPR's SAE team using DEP and without DEP be investigated and compared. These two geometries will be studied in detail to understand their potential, limitations, and possible future developments for DEP application on aircraft.

Objectives

The exploration and examination of DEP will change the aerodynamics of an aircraft by knowing how they respond to lift and drag, which are vital factors when flying. The study of this geometry will help produce a valid method to predict the effects of utilizing CFD (Computational Fluid Dynamics) to design a more efficient and improved aircraft performance.

Contributions

The use of aerodynamic enhancements due to the use of DEP will improve the performance and efficiency of the aircraft by reducing the distance for takeoff and landing by improving lifting on the aircraft, reducing noise with zero emissions, and reducing the cost of operation of the aircraft. It will also help achieve better low-speed efficiency and cruise efficiency at higher speeds.

METHOD

This project aims to produce a valid method to predict the effects of utilizing CFD on the design of DEP aircraft. Using the aircraft design model of the 2018 Capstone of PUPR's SAE Aero-design team with DEP aircraft and one aircraft design without DEP (No DEP) will be analyzed, explored, examined, and discussed in detail [2]. The study will be conducted for half a wingspan, meaning that one side of the wings will be analyzed using steady CFD, and the propellers will be modeled as actuator disks [3] [4]. The wing design utilizes a low-speed airfoil that is the GA(W)-2, and the propellers are twelve (12) equally spaced 2-bladed 6-inch diameter x 9-inch pitch propellers with a blade angle(β) at 75% of 32.48 degrees in front of the wings' leading edge (LE). To calculate the blade angle (β) at 75% radius of the propeller, the following equation is used:

$$\text{Blade angle } (\beta_{0.75}) = \left(\frac{\text{pitch}}{0.75 \times \pi \times D} \right) \quad (1)$$

Where: *pitch* is the distance that a propeller theoretically advances during one revolution, π is Pi (3.14), and D is the diameter of the propeller [5]. For the study, there will be six (6) propellers; as mentioned earlier, it will be a half wingspan analysis. Figures 1 and 2 show a representation of the airfoil and the propeller in SolidWorks.

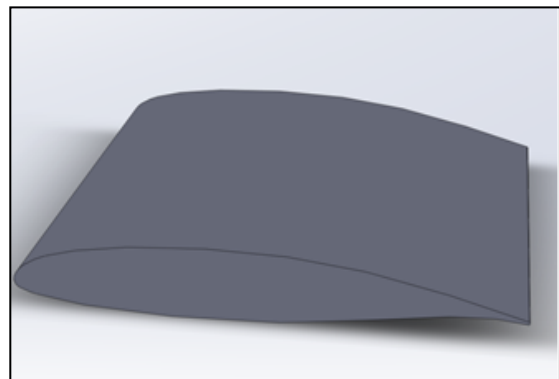


Figure 1
Airfoil GA(W)-2



Figure 2
2 Blade Propeller 6x9

The comparison of the benefits and disadvantages of each geometry will be discussed. Using an airfoil section, there is a point on any airfoil about which the pitching moment remains nearly constant as the angle of attack is changed, and this is called the aerodynamic center and is at $\frac{1}{4}$ or 25% back from the airfoil leading edge, that is, the quarter-chord point, and it is chosen as our reference location for airfoil lift, drag, and pitching moment data. The calculations of the lift coefficients, drag coefficients, and moment coefficient, or pitching moment, will be generated by using the following equations:

$$C_l = \frac{\text{Section lift}}{qc} \quad (2)$$

$$C_d = \frac{\text{Section drag}}{qc} \quad (3)$$

$$C_m = \frac{\text{Section moment}}{qc^2} \quad (4)$$

Where: C_L is the lift coefficient, C_D is the drag coefficient, C_M is the moment coefficient, q is the dynamic pressure = $\rho V^2/2$, ρ is the air density, V is the freestream airspeed, C_L is the lift coefficient, and c is the chord length. Note that two-dimensional airfoil characteristics are denoted by lowercase subscripts (ex., C_l), whereas the three-dimensional wing characteristics are denoted by

uppercase subscripts (ex., C_L) [5]. This will be done at different angles of attack (AOA). A table of the percentage of difference for each coefficient vs the angle of attack will be presented to better understand the use of DEP and those without it.

In addition, graphs of pressure coefficient for the different models, drag coefficient vs angle of attack, lift coefficient vs angle of attack, moment coefficient vs angle of attack, and graphs with streamlines of velocity magnitude will be discussed and analyzed to determine the differences between using DEP systems on an aircraft vs without it, No DEP.

The software will be used to analyze all the data, and the software will be Ansys Fluent to obtain Computational Fluid Dynamics (CFD) calculations. As previously stated, the objective is to help design a more efficient and improved aircraft performance using DEP, reduce the noise, and help the environment by reducing greenhouse gases. The purpose of this research is to investigate the merits of DEP for future aircraft concepts and development for commercially used aircraft.

RESULTS

The study was conducted for the half wingspan with the use of DEP using steady CFD and with the propellers modeled as actuator disks. It was compared without the use of DEP, which is the traditional method. Both models, DEP and No DEP, on Ansys were analyzed in Ansys Fluent as a 3d Transonic flow over a wing, utilizing a flow domain shape like a bullet, as seen in Figure 3. The conditions for both models were:

- Freestream velocity = 45 ft/s (foot per second)
- Air density = 0.00237689 slugs/ft³ (slugs per cubic foot)
- Air viscosity = 3.7373 x 10⁻⁷ slugs/ft/s (slugs per foot per second)
- Half wingspan of 3.54 ft (foot)
- Chord length: 0.7867 ft
- Wing Area: 2.784918 ft

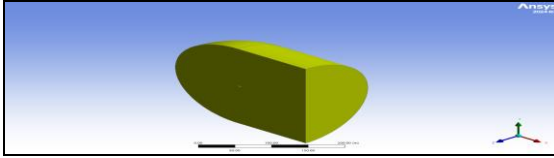


Figure 3
Flow Domain

For the DEP model, propellers were enclosed with an actuator disk of 6 in, rotating at a speed of 8850 rpm (revolutions per minute), which equals 926.76983 rad/s (radians per second). The analysis for both models was performed at different AOA (Angle of Attack), which were 0, 2, 4, 6, 8, 10, and 12 degrees.

Lift, Drag, and Momentum Coefficients vs AOA

The results for C_L and C_D for each model can be seen in Tables 1 and 2 below, along with another parameter evaluated, which was the moment coefficient (C_M) between both models.

Table 1
Results for DEP Model C_L , C_D , and C_M at Different AOA

AOA (degrees)	C_L	C_D	C_M
0	0.40437403	0.043834883	-0.109322
2	0.53763017	0.051333346	-0.1143207
4	0.62633697	0.068034624	-0.1135853
6	0.73055101	0.087398411	-0.1147219
8	0.83121181	0.11174679	-0.116436
10	0.92453951	0.14044837	-0.1178721
12	1.0136704	0.17418533	-0.1205252

Table 2
Results for No DEP Model C_L , C_D , and C_M at Different AOA

AOA (degrees)	C_L	C_D	C_M
0	0.36042344	0.023894741	-0.09843816
2	0.53207003	0.029438187	-0.1003034
4	0.67130821	0.041098112	-0.09611887
6	0.80123879	0.055787527	-0.09090482
8	0.89650843	0.073458181	-0.08169873
10	0.92101562	0.096470421	-0.07320874
12	0.89332783	0.12709044	-0.07426965

The aerodynamic behavior of the lift coefficient, drag coefficient, and moment coefficient as a function of the different angles of attack is seen in Figures 4, 5, and 6 for the DEP model and the No DEP Model. The table of the % increase of the DEP Model vs the No DEP model

for lift coefficients, drag coefficients, and moment coefficients is presented in Table 3. The lift coefficients of the DEP model are clearly increased as compared to the No DEP model at AOA of 0,2,10, and 12 degrees, but at 4, 6, and 8 are lower than the No DEP model. No DEP model lift coefficients stall at 10 degrees, and the DEP model is still going up. Since the lift coefficients for the No DEP model reach a maximum at around 10 degrees of AOA, and the DEP model does not reach a maximum at the same degrees of AOA. In percentage C_L , it is 11.49% at 0 degrees and 12.62% at 12 degrees, which are the maximum increased values, as shown in Table 3. For drag coefficients, the DEP model is higher than the No DEP model, representing that the use of propellers on the front of the wing causes this effect on the wing, which was expected, with a C_D with the highest 58.88 % difference at 0 degrees and the lowest 31.26 % at 12 degrees, as shown in Table 3. Showing that at higher AOA, the difference in C_D between models is less. For the moment coefficient, DEP has a clearly decreased value compared to the No DEP model. For the No DEP C_M stalls at 10 degrees, and for the DEP model, it is still going down and does not show a stall, as seen in Figure 6. There is an increase of C_M for the DEP model to a minimum of 10.48% and a maximum of 47.49% compared to the No DEP model, as shown in Table 3. These results make sense since the DEP having six propulsion engines near the wing can affect the pressure on it, making it more negative.

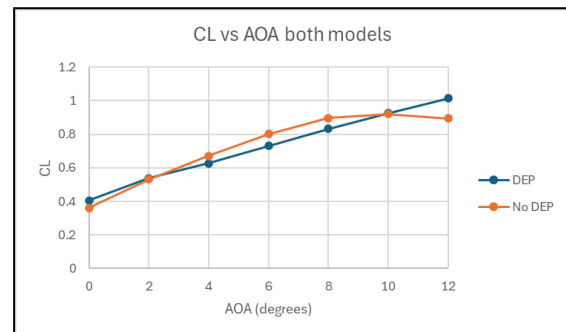


Figure 4
DEP Model and No DEP Model C_L Coefficients vs AOA Comparison

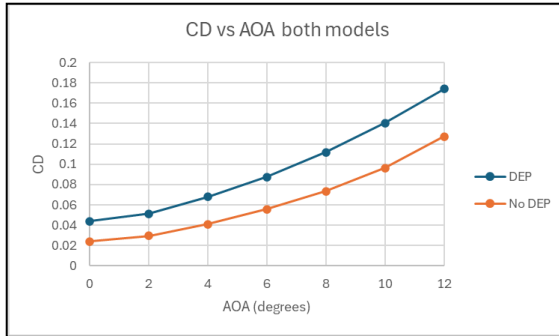


Figure 5
DEP Model and No DEP Model C_D Coefficients vs AOA Comparison

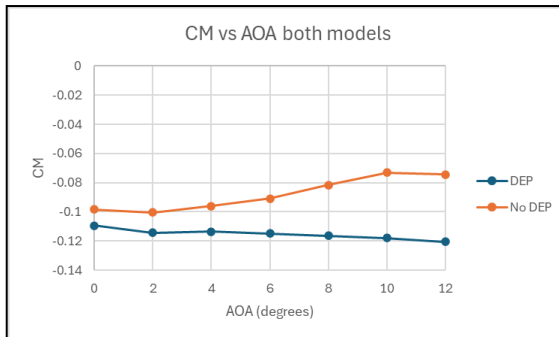


Figure 6
DEP Model and No DEP Model C_M Coefficients vs AOA Comparison

Table 3
Percentage Difference for DEP vs No DEP Model C_L , C_D , and C_M at Different AOA

AOA (degrees)	C_L % increased	C_D % increased	C_M % increased
0	11.49	58.88	10.48
2	1.04	54.22	13.06
4	-6.93	49.36	16.66
6	-9.23	44.15	23.17
8	-7.56	41.35	35.06
10	0.38	37.12	46.75
12	12.62	31.26	47.49

In Figures 4, 5, and 6, a side-by-side comparison of C_L , C_D , and C_M between the two models can be seen. The results shown in Figures 4, 5, and 6 illustrate that the performance of the DEP model is better than the No DEP model.

Pressure Coefficients

For pressure coefficients as a series of graphs extracted from Ansys Fluent to show the difference between models, these graphs will demonstrate the

difference between models for two different angles at 0 degrees and 12 degrees, respectively. That DEP model has higher pressure coefficients than the No DEP model. This can be seen in Figures 7, 8, 9, and 10.

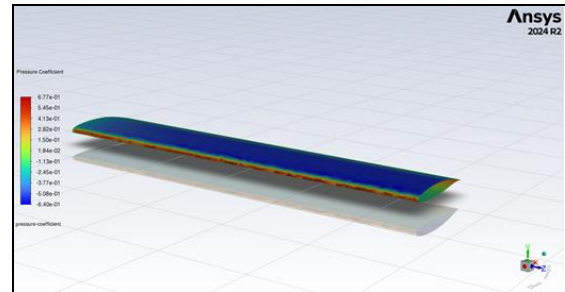


Figure 7
No DEP Pressure Coefficient at AOA of 0 Degrees

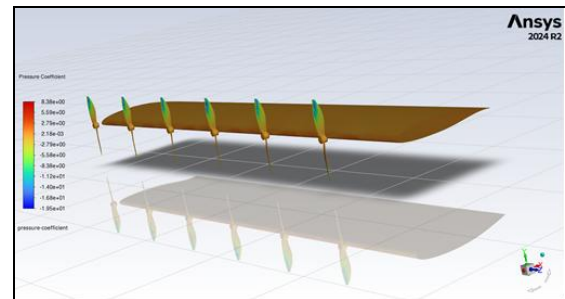


Figure 8
DEP Pressure Coefficient at AOA of 0 Degrees

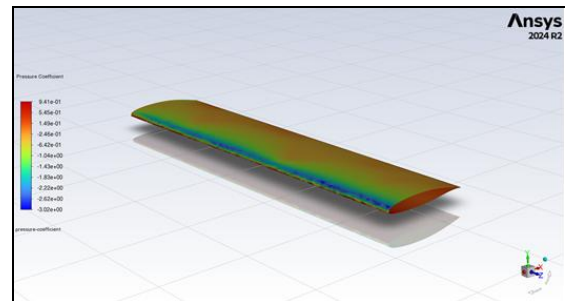


Figure 9
No DEP Pressure Coefficient at AOA of 12 Degrees

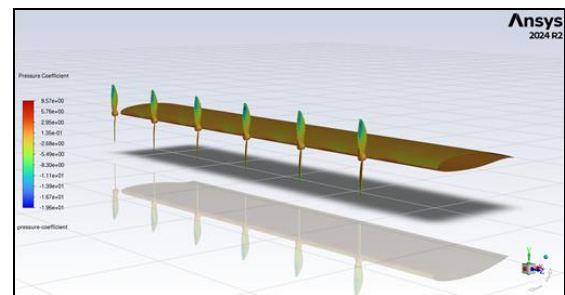


Figure 10
DEP Pressure Coefficient at AOA of 12 Degrees

Velocity Magnitude Streamlines

The velocity magnitude streamlines can be observed in Figure 11 for the DEP model. In the DEP model, it can be seen how the air velocity when it enters the actuator disks gets more velocity due to the rotation of the propellers.

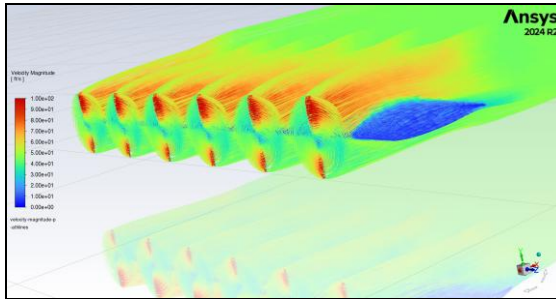


Figure 11
DEP Velocity Magnitude Streamlines

CONCLUSION

Through this project, using an actuator disk to represent the propellers on DEP Models proved to be a valid method to predict the effects of utilizing Computational Fluid Dynamics to design a more efficient and improved aircraft performance by knowing how they respond to lift and drag, which are vital factors when flying. It was proven that using DEP on a wing vs without DEP relative to normal airfoil geometry will increase the C_L and C_D . For the lift coefficient, there was a significant increase for DEP on a wing vs without DEP at 0 degrees of angle of attack by 11.49% and on 12 degrees of angle of attack by 12.62%. For 4 to 8 degrees, there was a decrease between -6.93% to -9.23%, which was the lowest at 6 degrees angle of attack. We were expecting higher lift coefficients around the entire curve for the range of angle of attack, but there is a light increase. For drag coefficients, there is an increase from 31.26% to 58.88% making the highest at 0 degrees of angle of attack and the lowest at 12 degrees of angle of attack. That is the expected effect since having six propellers on the wing can cause more drag than only having the wing itself. For moment coefficients, we have a decrease around the entire range of angles of attack from 0 to 12 degrees, with

the maximum decrease at 12 degrees with 47.49% and the lowest increase at 0 degrees with 10.48%. This was expected because having propellers in front of the wing can change the center of pressure, as seen on the pressure coefficient graphs in Figures 7, 8, 9, and 10.

The two geometries were studied in detail to understand their potential, limitations, and possible future developments for DEP application on aircraft. The study opens the door for CFD analysis to predict DEP configuration essential values for design. With the increased lift and drag on the DEP configuration on the aircraft, it can have shorter wings than a normal configuration (No DEP) wing at lower velocities. It is the same concept as flaps on a wing that change the wing camber in the trailing edge to increase lift and drag to take off with a shorter distance and at a low speed. Making DEP and aircraft with lower takeoff/landing field length, resulting in low-noise and low-maintenance aircraft by having better aerodynamics and being cleaner to the environment.

Further analysis of this concept should be continued, as the current trend of turbo-prop engines will eventually transition to another type of energy source, due to fuel shortage and unaffordable fuel prices. Electrical aircraft will show promising and cost-effective technology once future battery density discoveries continue to govern the engineering of the future. One factor that could be expanded for this project is the placement of the propellers. Putting propellers in different arrangements, further from the wing, a higher or lower placement on top of the wing, like a turbine propulsion system, could result in more benefits for the aerodynamics of the wing. Other effects to be studied are different propeller blade shapes and types with respect to the wing. Results showed a slight improvement in lift coefficients due to DEP that increased at slower aircraft velocities, as predicted. Further studies could identify a perfect placement of the propellers and blade shape to obtain the ideal distributed configuration for maximum efficiency and elevate the lift coefficient further. The study was conducted for half a

wingspan, meaning that one side of the wings was analyzed. Another study can be done by using the entire wingspan and seeing all the effects. I am certain that the results are going to be breathtaking. The study proved that it's necessary to continue studying more profound DEP with an actuator disk for the propellers and compare the 3D results of C_L , C_D , and C_M with the results obtained from the CFD analysis.

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