

## Abstract

To reduce the 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 Distributed Electric Propulsion (DEP), which significantly enhances aircraft performance by coupling propulsion and air dynamics by distributing adequately designed propellers along a lifting surface. This study aims to produce a valid method to predict the effects of utilizing Computational Fluid Dynamics (CFD) 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.

## Introduction

This project intends to gather all the advantages of electric motor designs, implement them in a small aircraft that flies at low velocities (DEP), and compare it to a standard aircraft. The small aircraft will be the one designed by PUPR's SAE Aero-design team for their 2018 Capstone project. The DEP design and the design without DEP will be analyzed and compared 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.

## Background

There are many propulsion systems, and one of them is distributed propulsion (DP). 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 DEP, where the propulsors that produce thrust on the DEP system do not use a mechanical driveshaft or any mechanical power source. 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, 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 it uses electric motor and energy storage technologies, resulting in an extremely quiet system and zero vehicle emissions.

## Problem

The 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 to design a more efficient and improved aircraft performance. 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.

## Methodology

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) was analyzed, explored, examined, and discussed in detail.[2] The study was conducted for half a wingspan, meaning that one side of the wings was analyzed using steady CFD, and the propellers were modeled as actuator disks.[3] [4] The wing design utilizes a low-speed airfoil that is the GA(W)-2, and the propellers are six (configuration for half wingspan) equally spaced 2-bladed 6-inch diameter x 9-inch pitch propellers with a blade angle( $\beta$ ) at 75% of 32.48 degrees in front of the wings' leading edge (LE). To calculate the blade angle ( $\beta$ ) at 75% radius of the propeller, the following equation was used:

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

Where:  $\text{pitch}$  is the distance that a propeller theoretically advances during one revolution,  $\pi$  is Pi (3.14), and  $D$  is the diameter of the propeller.[5] 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 was 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, were generated by using the following equations:

$$C_l = \frac{\text{Section lift}}{qc} \quad (2) \quad C_d = \frac{\text{Section drag}}{qc} \quad (3) \quad C_m = \frac{\text{Section moment}}{qc^2} \quad (4)$$

Where:  $C_L$  is the lift coefficient,  $C_D$  is the drag coefficient,  $C_M$  is the moment coefficient,  $q$  is the dynamic pressure =  $\rho V^2/2$ ,  $\rho$  is the air density,  $V$  is the freestream airspeed,  $C_L$  is the lift coefficient, and  $c$  is the chord length. This was done at different angles of attack (AOA). The software used is Ansys Fluent to obtain CFD calculations. The Analysis is a 3d Transonic flow over a wing, utilizing a flow domain shape like a bullet. The conditions for both models are:

- Freestream velocity = 45 ft/s (foot per second)
- Air density = 0.00237689 slugs/ft<sup>3</sup> (slugs per cubic foot)
- Air viscosity = 3.7373 x 10<sup>-7</sup> 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

For the DEP model, propellers enclosed with the actuator disk were rotating at a speed of 8850 rpm (revolutions per minute).

## Results and Discussion

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 1, 2, and 3 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 1. 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. 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. 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 3. 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. These results make sense since the DEP having six propulsion engines near the wing can affect the pressure on it, making it more negative. The results shown in Figures 4, 5, and 6 illustrate that the performance of the DEP model is better than the No DEP model.

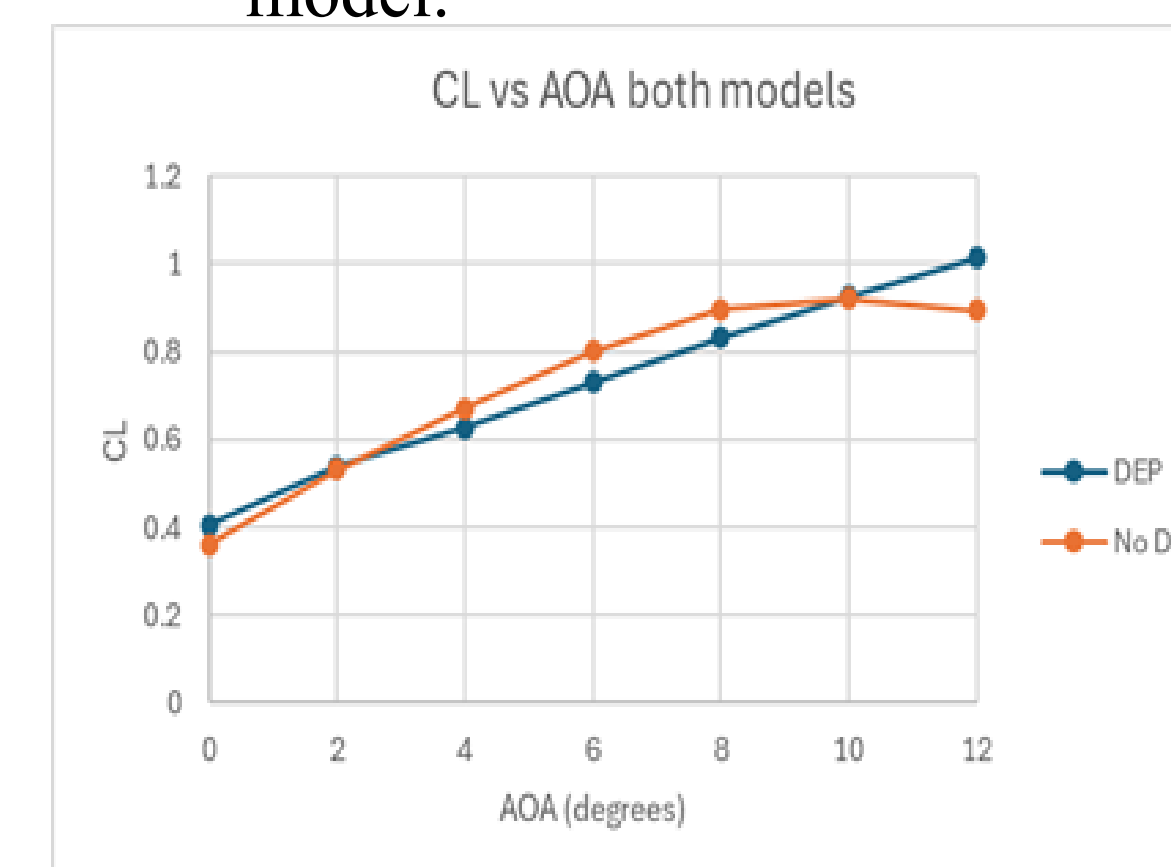


Figure 1  
DEP Model and No DEP Model  $C_L$  Coefficients vs AOA

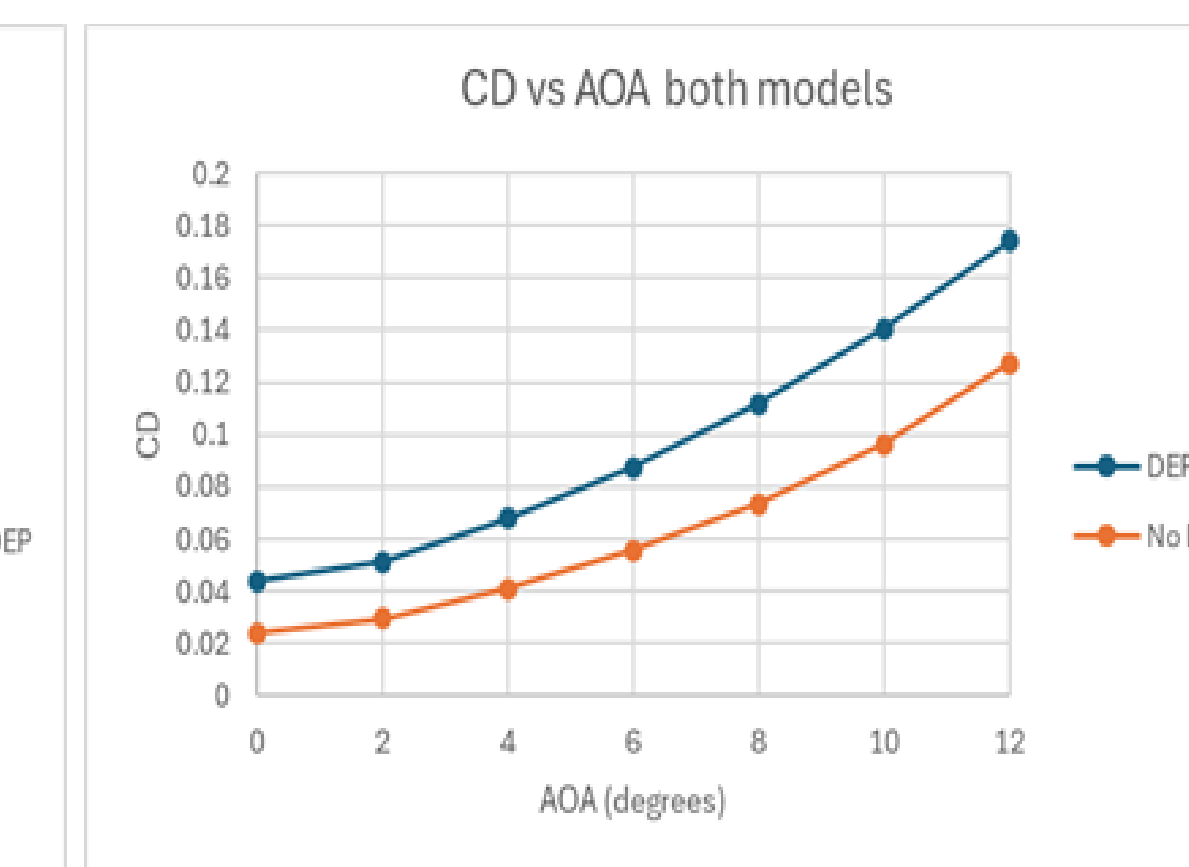


Figure 2  
DEP Model and No DEP Model  $C_D$  Coefficients vs AOA

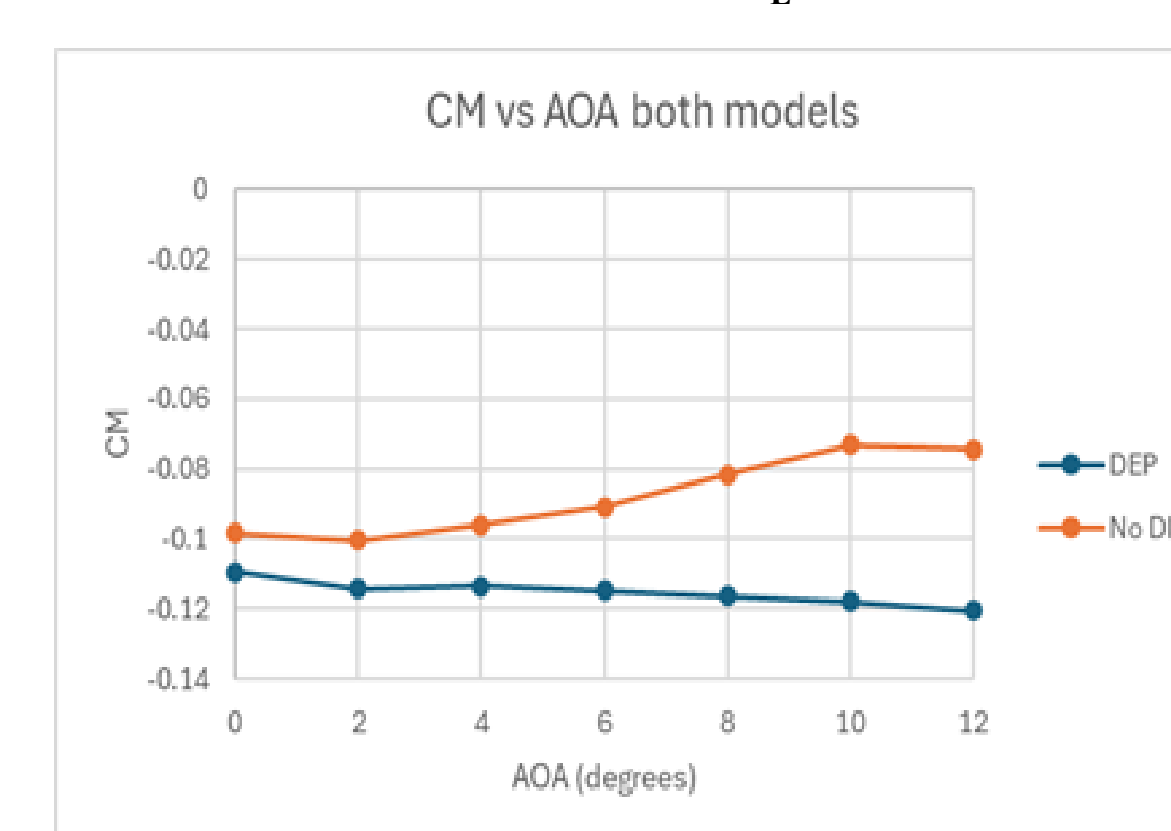


Figure 3  
DEP Model and No DEP Model  $C_M$  Coefficients vs AOA

Table 1  
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

For pressure coefficients, DEP model has higher pressure coefficients than the No DEP model. As shown on Figure 4 and 5. The velocity magnitude streamlines can be observed in Figure 6 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.

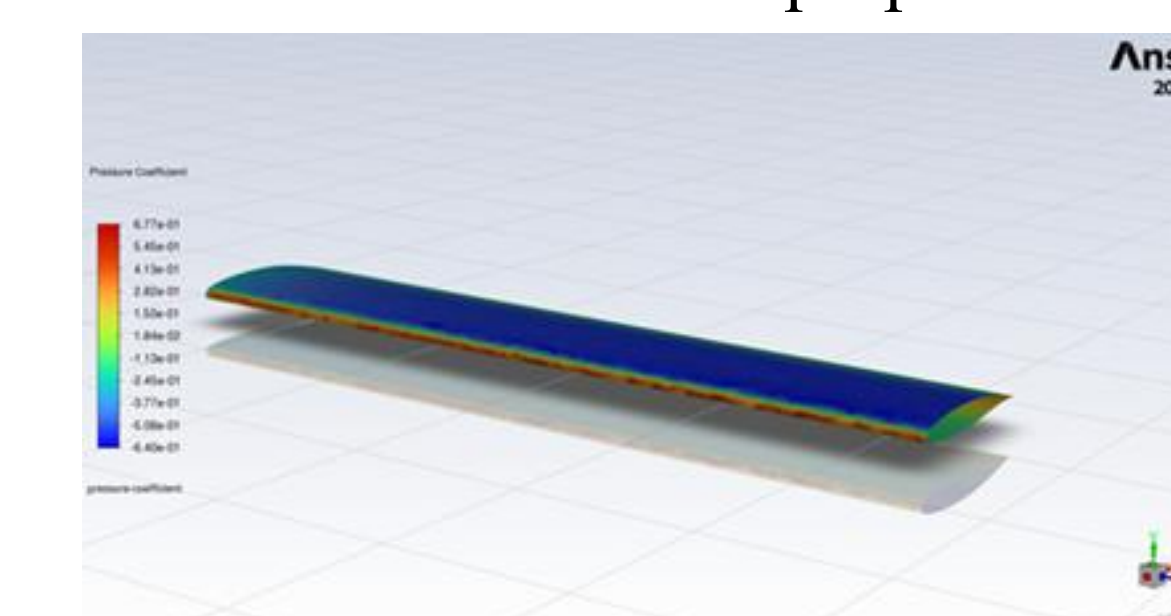


Figure 4  
No DEP Pressure Coefficient

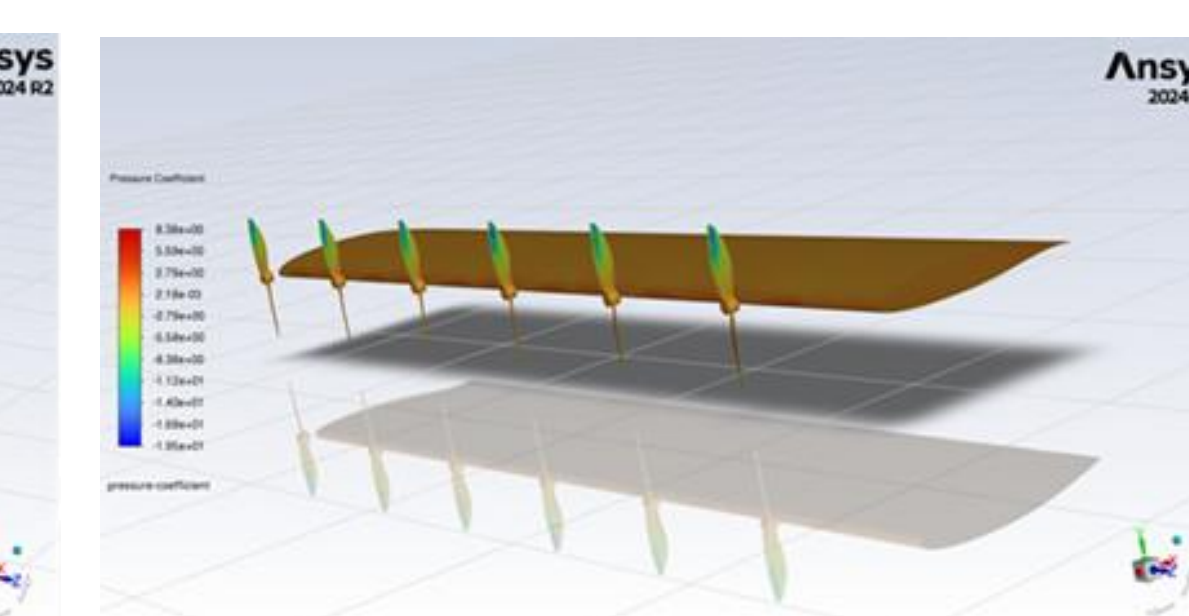


Figure 5  
DEP Pressure Coefficient

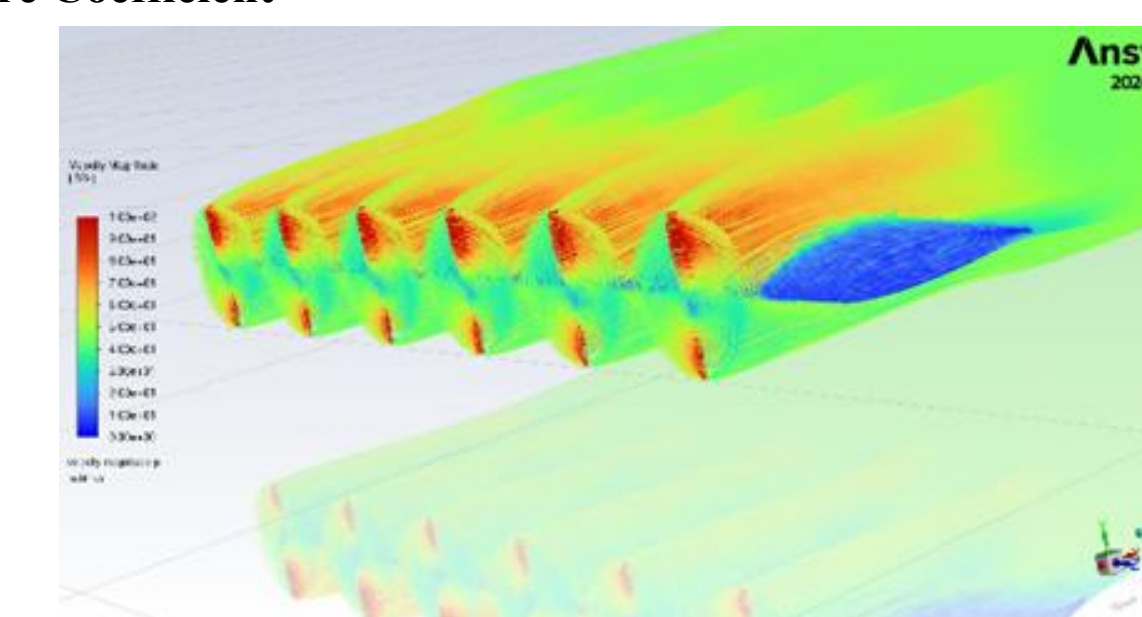


Figure 6  
DEP Velocity Magnitude Streamlines

## Conclusions

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 CFD 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  $C_D$ . The lift coefficient was slightly increased on some angles of attack. We were expecting higher lift coefficients around the entire curve for the range of angle of attack. For drag coefficients, there was an increase at all angles 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 as expected because having propellers in front of the wing can change the center of pressure. 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. 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.

## Future Work

One factor that could be expanded for this project is to study different propeller blade shapes and types with respect to the wing. Further studies could identify a perfect placement of the propellers, further from the wing, or a higher or lower placement on top of the wing, to obtain the ideal distributed configuration for maximum efficiency and elevate the lift coefficient further. 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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