

Efficiency Improvements for eVTOL Based on Vented Duct Geometry

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Abstract. In reality, eVTOL aircraft have substantial promise in revolutionizing transportation within cities and other short distances due to their ability to take off in confined spaces and the low emissions and noise generated with eVTOL aircraft. However, eVTOL aircraft are still limited by battery technology. Current battery systems draw inspiration from the automotive sector and are capable of ranges of up to 150 miles. Continuing to increase efficiency will be beneficial to allow eVTOL aircraft to be used in applications where greater range is needed, e.g., search and rescue and in the general UAM application to further shorten downtime experienced for charging. In this study, a novel vented duct geometry utilizing entrainment is investigated and found to have doubled thrust generated. The test and reference duct were constructed utilizing a modified NACA airfoil and tested with Simscale CFD software. The vented duct geometry was found to produce a significant thrust increase over a reference duct. Nevertheless, the need was found for optimizing the vent geometry as eddy currents were observed to appear and thus limit the amount of air entrained. Other analysis methods including PIV were suggested to optimize the geometry to prevent eddy currents. Adopting the geometry would allow for increases in range without the need for complex additional energy stores (e.g., hydrogen), decreasing cost and complexity needed to optimize efficiency of eVTOL aircraft. Successfully implementing this propulsor geometry would unlock applications like regional routes and longer endurance/range operations.

Keywords: Vent duct geometry, eVTOL, Simscale simulation.

1. Introduction

The concept of Electric Vertical Takeoff and Landing (eVTOL) aircraft has grown significantly owing to advancements in battery and motor technology [1, 2]. Advancements in battery technology from the automotive sector such as lithium-ion batteries and silicon anode technology have allowed companies like Lilium to significantly lower charging times and increase range of their eVTOL aircraft [3]. Further advancements leveraging hydrogen-electric technology has enabled significant expansion of range. For example, Joby Aviation recently demonstrated a 523-mile flight using a hybrid hydrogen-electric power system, more than tripling the range of their S4 aircraft, which has an electric only range of 150 miles [4, 5].

Despite the significant range extension possible with hydrogen-electric power, hydrogen fuel cell technology encounters difficulties related to fueling, as specialized cryogenic infrastructure is required to store the large amounts of hydrogen needed to power eVTOL aircraft due to hydrogen's low volumetric energy density (around 8.4 MJ/liter compared to 34.7 MJ/liter for Jet A1) [3]. This infrastructure would be far more difficult to develop than already widely developed electric charging infrastructure for EV automobiles leveraging common standards such as CCS, and as such, impede the widespread adoption of hydrogen-electric power systems [6-8].

Therefore, a need arises to better optimize the range and efficiency of eVTOL propulsion systems to enable eVTOL aircraft to serve longer regional routes on current and near-future battery technology [9]. Much work has been done in optimizing electric propulsions systems using the basis of boundary layer ingestion (BLI) [10]. For example, the NASA Glenn Research center has developed the STARC-ABL concept, which couples electric propulsion with conventional turbofan propulsion to significantly reduce fuel burn and emission levels, reducing required power at cruise by 6 to 9 percent [11]. In addition to BLI, other optimization methods include advanced aerodynamic shaping and the use of distributed propulsion systems. The Lilium Jet leverages 36 propulsion pods distributed around

the wings and canards to improve reliability in the case of an engine failure and to optimize efficiency utilizing ducted fans with an adjustable exit nozzle diameter to increase thrust produced through different regimes of flight [12]. The ducted propulsion pod approach brings further advantages of noise dampening and the ability to contain blade fragments in the event of a blade off scenario due to mechanical stress or impact with foreign object debris. As such, ducted electric propulsion is a promising architecture for eVTOL aircraft [13]. The potential for more efficient and safe propulsion by way of ducted propulsors has also motivated research into ducted propulsors utilizing thrust augmentation to further increase efficiency. Garret finds that utilizing a co flow slot-jet duct geometry enables passive thrust augmentation on the basis of entrainment, with the biggest contributing factor to an increase of thrust being the angle of attack of the airfoils that make up the walls of the duct [14].

This study aims to investigate this method of thrust augmentation for an electric ducted fan (EDF) using CFD simulations. The potential for thrust augmentation will be ascertained through comparing thrust and velocity calculations obtained in software with those of a control duct design with no vents for entraining air. The EDF setup investigated in this work is modeled with implementation envisioned in eVTOL aircraft similar to the Lilium Jet. This research aims to examine novel ways of increasing efficiency of existing eVTOL aircraft while maintaining an electric architecture, making the widespread adoption of these efficiency modifications possible.

2. Experimental Setup

Both the test duct and control duct were modeled in Fusion 360 using the NACA 2630 airfoil generated through the Fusion 360 Airfoil Generator utility as the basis for the cross section. The high-pressure side was the outside of the duct while a section of the low-pressure side at 50% chord length from the leading edge was mirrored across the x axis to form the inside of the duct. Additionally, a vent was created with the entry point to the main duct located behind the maximum thickness of the duct formed by the NACA airfoil as depicted in Fig. 1

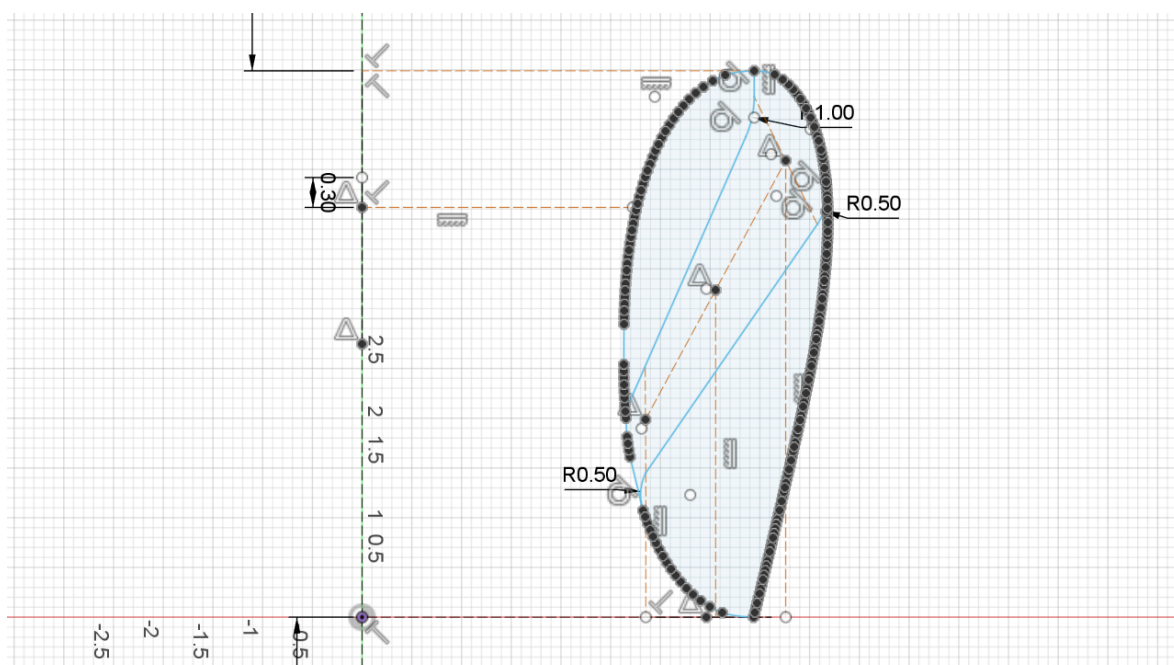


Fig. 1 The configuration for the airfoil (Photo/Picture credit: Original).

In this study, SimScale's Computational Fluid Dynamics (CFD) functionality was employed to analyze the control and test ducts. Based on the performance of the fastest eVTOL aircraft currently undergoing flight tests, the Lilium Jet at 175 mph top speed, an incompressible flow assumption was adopted. Given that the design aims for integration with existing eVTOL aircraft, evaluating its performance within this flight regime is deemed appropriate. The ducts were tested at a fan speed of 77 m/s (i.e., 175mph). Boundary conditions for the flow region were established as slip walls while

a momentum source located at the center of the duct was used to obtain the airflow. A steady-state simulation was conducted using the k-omega SST turbulence model. The duct boundary conditions were set to no-slip walls. Meshing was accomplished using the hex-dominant algorithm in Simscale, with the final mesh containing 1.1 million cells. Probing points were strategically placed 0.2 m in front of the duct entrance, at the origin (inside the duct), and 0.15 m behind the duct to measure velocity in the Z direction. These probe points recorded data every 10 simulation steps, while the overall simulation duration was set to 300 seconds.

Entrainment is the process by which pressure gradients cause fluid adjacent to a moving fluid to be engulfed into the flow, leading to an increase in mass of the primary flow, creating a passive thrust augmentation. In the situation investigated in this work, a region of lower pressure is created as the primary airflow within the duct accelerates. This lower pressure allows atmospheric air to be drawn towards the primary airflow. The general thrust equation defines thrust force as:

$$F = \dot{m}_e v_e - \dot{m}_0 v_0 + (p_e - p_0)A_e \tag{1}$$

Analyzing the equation, it demonstrates that to increase thrust force, a system can either, increase \dot{m}_e as much as possible or make the exit velocity as high as possible. After the setting, one runs the simulation and analyze the results after convergence.

3. Results and Discussion

The test duct was observed to increase velocity by 21.2 m/s compared to the increase observed by the control duct, 3.4 m/s, demonstrating an increase in thrust with the augmentation method. The velocity graphs of the probe points are shown in Fig. 2. In the test duct, conditions for entrainment can be seen to be present when the pressure distribution is analyzed. A low pressure zone is formed within the duct while the ducts remain at a higher pressure, open to the atmosphere as presented in Fig. 3. Thus, air is able to follow the pressure gradient and thus become entrained.

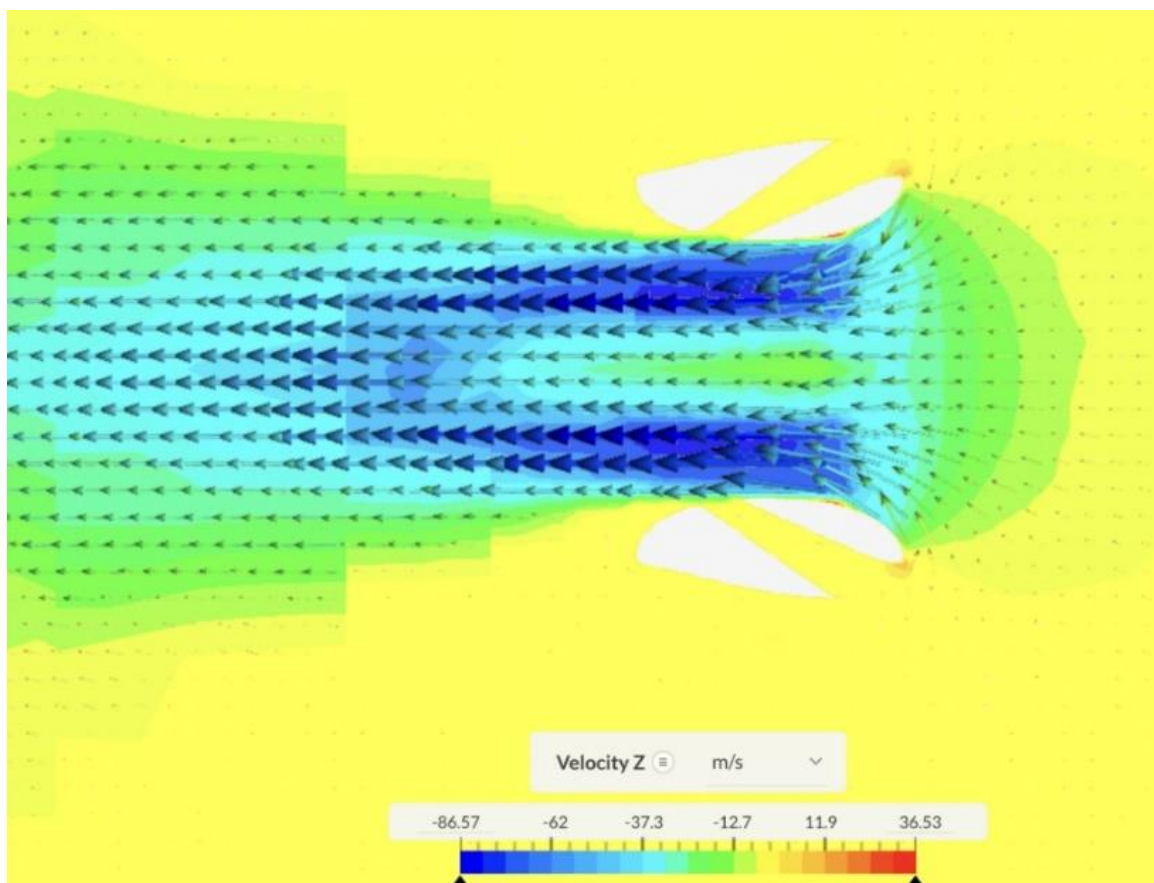


Fig. 2 Velocity graphs for test duct (Photo/Picture credit: Original).

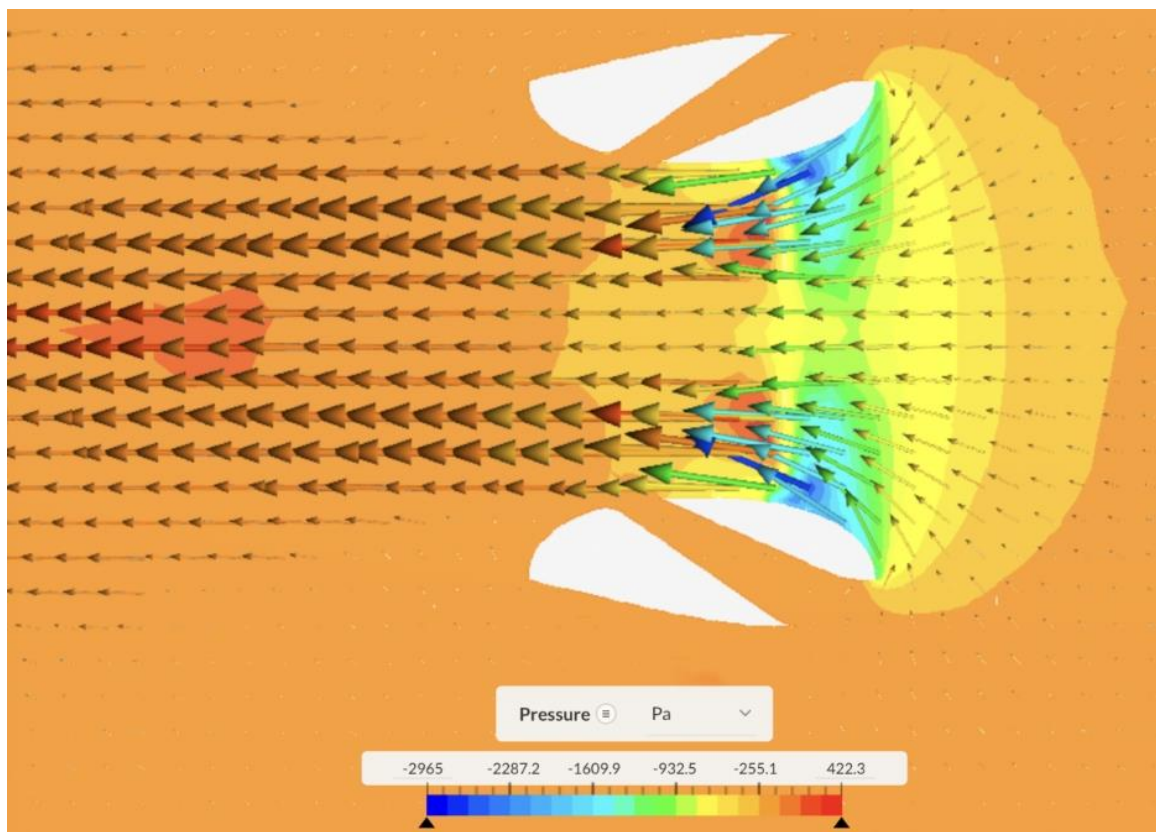


Fig. 3 Pressure graphs for test duct (Photo/Picture credit: Original).

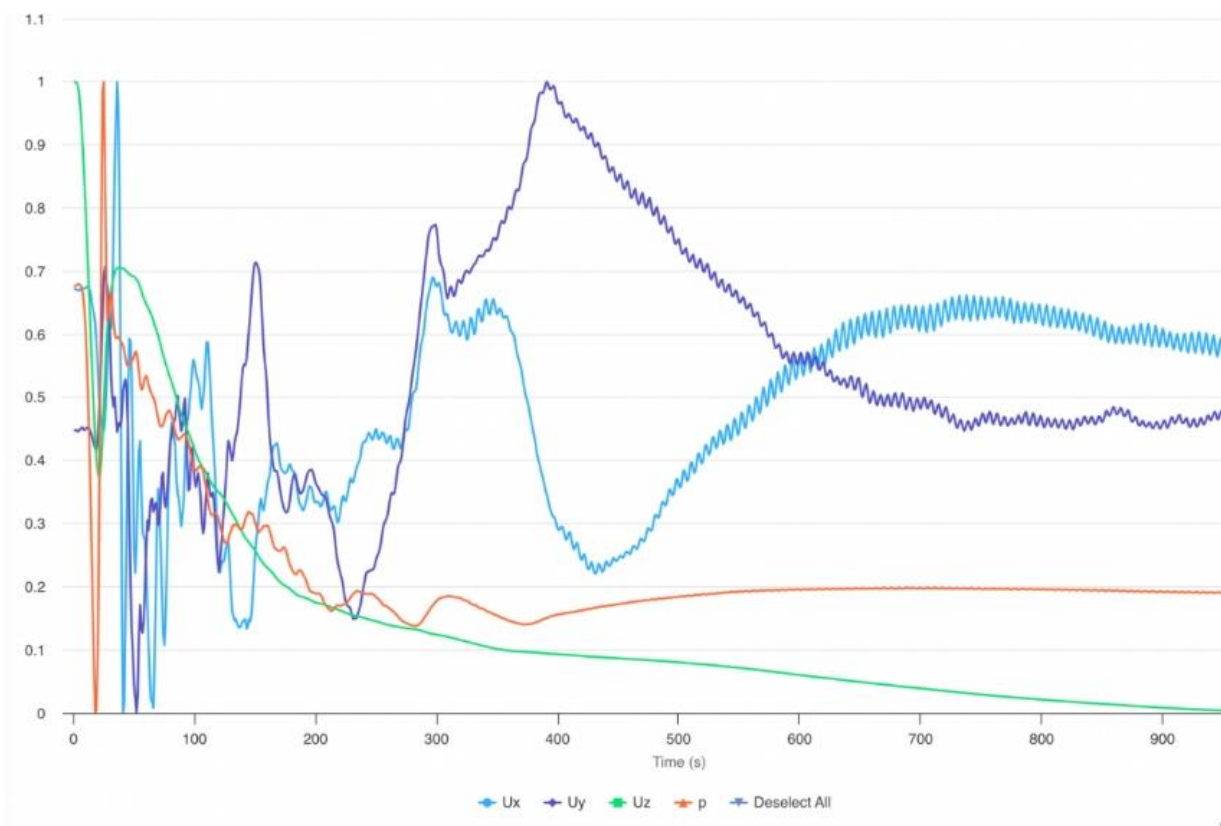


Fig. 4 Convergence results for domain (Photo/Picture credit: Original).

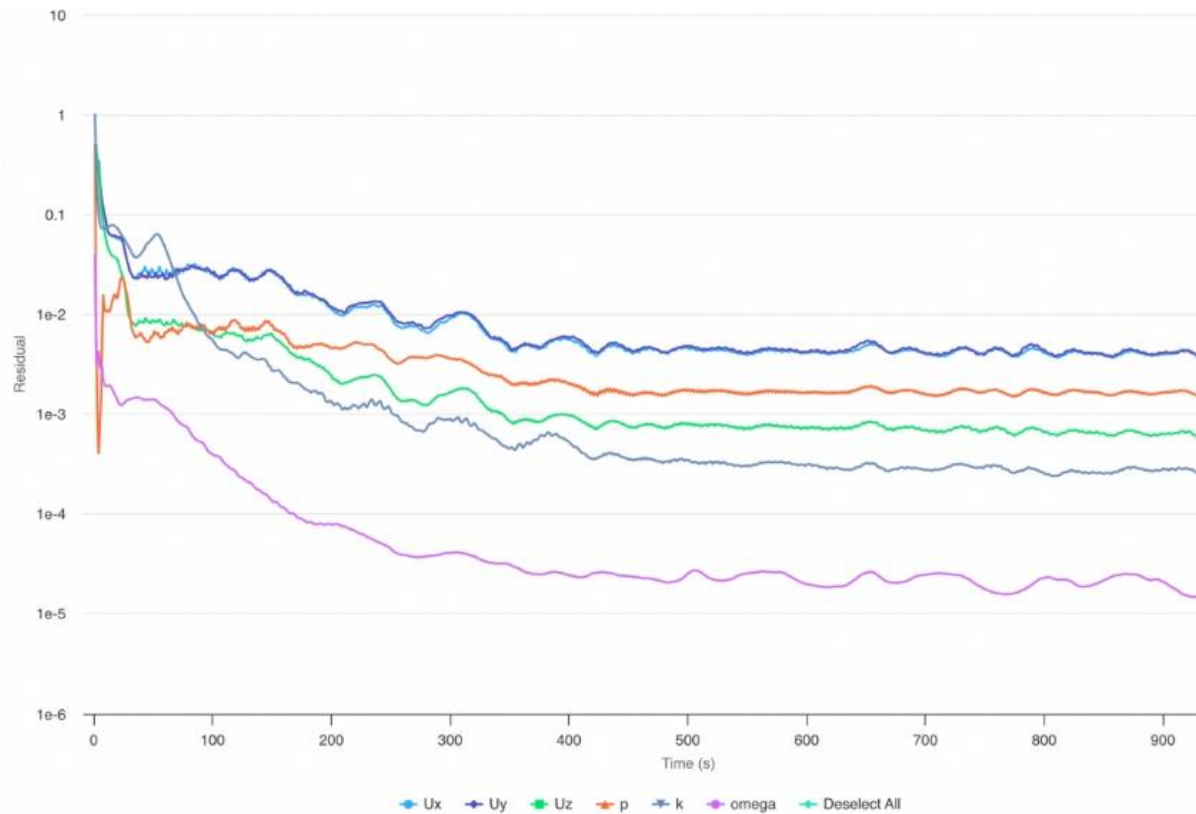


Fig. 5 Convergence results for residual (Photo/Picture credit: Original).

Convergence for the test duct simulation can also be seen to be achieved, with acceptable convergence of the domain and residuals (as presented in Fig. 4 and Fig. 5). A similar pressure distribution can be observed with the control duct, causing acceleration of the airflow, and convergence for the control duct simulation can also be seen to be achieved, with acceptable convergence of the domain and residuals.

Though results obtained from software demonstrate that a significant increase in thrust can be obtained through duct geometries utilizing entrainment thrust augmentation, further testing still needs to be conducted to better optimize these geometries. One point of optimization is the pressure differential generation between the inside and outside of the duct while preventing eddy currents from forming. The vectors representing the flow of air that enter the duct through the vents are shown to be significantly smaller than those of the freestream, and as such the effect of entrainment is limited in this regard. For a more detailed analysis, techniques such as PIV could be used to better visualize the flow and optimize the geometry of the vents to enable more complete entrainment and a higher thrust augmentation.

4. Conclusion

To sum up, in this work, the vented duct geometries for thrust augmentation through entrainment were investigated. The test duct utilizing thrust augmentation was found to increase airspeed from 19.4 m/s at the entry point to 40.6 m/s at the exit, a 21.2 m/s or 109% increase in velocity, demonstrating the effect of thrust augmentation. CFD simulations also revealed the formation of eddy currents and the relatively limited amount of air that is entrained through analysis of the vector fields in the simulation. For further optimization, methods like PIV for flow visualization were proposed to better understand formation of currents and to optimize the vent geometries to prevent this. This work is significant due to the possibility for implementation in existing eVTOL aircraft that utilize ducted propulsors. Adopting this vented duct geometry would allow further efficiency gains of eVTOL aircraft without expensive supplemental energy sources like hydrogen. While more investigation needs to be conducted on optimizing these geometries, thrust augmentation through entrainment

proves to be a promising means of enabling the next generation of eVTOL aircraft to realize a cleaner and more efficient electric aviation landscape.

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