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DESIGN AND PARAMETERS IMPACT EVALUATION ON THE PERFORMANCE OF AN EVTOL AIRCRAFT

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Abstract. *Electric vertical takeoff and landing (eVTOL) aircraft are undergoing significant development worldwide, with various configurations being explored. The objective of this study is to contribute to the advancement of its efficiency and sustainable aviation solutions by optimizing the design of eVTOLs during the conceptual phase and assessing their performance from an efficiency standpoint. It is employed an open-source framework called FLOWUnsteady, which utilizes the reformulated vortex particle method (rVPM) for unsteady aerodynamics and aeroacoustics. This framework enables us to evaluate the aerodynamic forces acting on the aircraft during a typical mission and analyze the effects of different aerodynamic factors on various eVTOL structures. Additionally, the research aims to achieve a reasonable eVTOL configuration by examining its energy and aerodynamic efficiency in a regular mission. The study endeavors to offer insights for future research and assist in engineering decision-making. To accomplish this, it is developed a comprehensive sizing model for eVTOL aircraft, aiming to offer a clear and understandable framework that guides the design and evaluation of these aircraft.*

Keywords: *Design, Parameters, eVTOL, Aerodynamics, rVPM.*

1. INTRODUCTION

Emerging advancements in electrification, automation, and related technologies are opening up new possibilities for on-demand air mobility, aircraft design, and business models. Urban air mobility (UAM) envisions a safe, affordable, sustainable, and easily accessible air transportation system within metropolitan areas, catering to passenger mobility, goods delivery, and emergency services (Cohen *et al.*, 2021). The advent of electric vertical takeoff and landing (eVTOL) aircraft has generated considerable interest, with several companies planning to launch commercial services in the near future. These compact, cost-effective, and highly maneuverable aircraft, also known as urban air mobility or flying cars, are being considered for diverse applications like air taxis, emergency medical transport, sightseeing vehicles, and rural transportation (Mihara *et al.*, 2021; Brown and Harris, 2020; Daskilewicz *et al.*, 2018). By eliminating the need for long runways, eVTOL aircraft have the potential to revolutionize urban mobility, alleviate congestion, and reduce pollution emissions. However, the widespread adoption of eVTOL aircraft as a mainstream mode of transportation faces numerous challenges and uncertainties.

One crucial aspect in the pursuit of the best configuration for VTOL-capable aircraft is design optimization (Finger *et al.*, 2017). The interaction between aerodynamics, propulsion, and structures poses a complex and unsteady problem to solve. Predicting the unsteady aerodynamic interactions between rotors, wings, and fuselage in eVTOL aircraft, for example, is highly challenging (Anderson *et al.*, 2023; He and Rajmohan, 2016; Bae *et al.*, 2019). To address this need, both academia and industry have recently turned their attention to the vortex particle method (VPM) as a promising solution (Alvarez *et al.*, 2022; Alvarez and Ning, 2019, 2022). The FLOWUnsteady framework, based on the reformulated vortex particle method (rVPM), offers an open-source variable-fidelity platform for analyzing these interactions and evaluating the initial design of eVTOL aircraft (Alvarez *et al.*, 2022).

Along those lines, this study specifically investigates the impact of design choices on the aircraft's aerodynamic performance. The objective is to gain insights into how different configurations influence aerodynamic forces and characteristics. By assessing and evaluating the aerodynamic effects of these different configurations, we aim to provide insights into the optimization and improvement of eVTOL aircraft design.

2. MODELING METHODOLOGY

This research comprises two key components: the aerodynamic modeling and the sizing approach. In Section 2.1, the aerodynamic modeling is presented, considering the application of the FLOWUnsteady as a solver for the aerodynamic analysis and to predict the aerodynamic forces and coefficients.

2.1 Aerodynamic modeling

The aerodynamic modeling is performed using the Meshless Large Eddy Simulation (LES) with Immersed Vorticity, which has been introduced by Alvarez *et al.* (2022). The Meshless LES approach offers advantages over traditional mesh-based methods by eliminating the need for structured grids and utilizing Lagrangian particles to represent the flow field Alvarez (2022). This enables accurate simulation of the intricate interactions between rotors, wings, and the fuselage of eVTOLs with improved efficiency.

The vorticity of solid boundaries can be immersed into the LES-filtered Navier-Stokes equations by decomposing the filtered vorticity field $\bar{\omega}(x, t)$ into a free-vorticity field $\bar{\omega}_{\text{free}}(x, t)$ and a bound-vorticity field $\bar{\omega}_{\text{bound}}(x, t)$. Discretizing both components with vortex particles, it follows:

$$\bar{\omega}(x) = \sum_p \Gamma_p \zeta_{\sigma_p}(x - x_p) + \sum_b \Gamma_b \zeta_{\sigma_b}(x - x_b) \quad (1)$$

Inverting the relation $\omega = \nabla \times u$, it is possible to obtain the velocity field that can be decomposed into a free-velocity field $\bar{u}_{\text{free}}(x, t)$ and a bound-velocity field $\bar{u}_{\text{bound}}(x, t)$, first and second term, respectively, in Eq. (2).

$$\bar{u}(x) = \sum_p g_{\sigma_p}(x - x_p) K(x - x_p) \times \Gamma_p + \sum_b g_{\sigma_b}(x - x_b) K(x - x_b) \times \Gamma_b \quad (2)$$

It is essential to firstly state that "p" refers to the particle and "b" to the boundary. With that stated, in the equations above, Γ_p represents vortex strength, x_p the position, ζ_{σ_p} the filter kernel of width σ and radial basis ζ_p , lastly $K(x)$ is equivalent to:

$$K(x) \equiv \frac{-1}{4\pi} \frac{x}{\|x\|^3} \quad (3)$$

Having those two terms stated, it is possible to say that the immersed vorticity impacts the existing vorticity and generates additional vorticity at the boundary through the diffusion of viscosity. In other words, the vorticity is formed within the boundary layer, accumulates along the surface, and eventually separates from the surface. In FLOWUnsteady simulations, instead of using the viscous diffusion equation to create vorticity, the shedding of immersed vorticity is prescribed at a specified trailing edge location, neglecting the wake resulting from flow separation, but still capturing the effects of flow separation on aerodynamic characteristics, such as the reduction in lift and the increase in pressure drag observed on a stalled airfoil.

3. Aerodynamic Analysis and Findings

This section presents the results of aerodynamic analysis and findings of a pre-sized eVTOL aircraft with an empty weight of approximately 500 kg and a cruise speed of 30 m/s. Firstly, the results are presented in their original form, without any modifications to their structure. Subsequently, the modified results, reflecting the impact of design changes, are presented for comparison and analysis. The main feature of the proposed eVTOL is the use of variable-pitch propellers, which allow for more efficient and flexible control of the thrust and power during different flight phases. More information about the original eVTOL airframe are presented in Table 1.

Table 1. Vehicle's airframe characteristics.

Fuselage		Main Wing		Tandem Wing	
Property	Value	Property	Value	Property	Value
Length	5.86 m	Span	5.86 m	Span	5.86 m
Height	1.87 m	Sweep	10°	Sweep	0°
		Taper Ratio	1	Taper Ratio	1
		Dihedral	5°	Dihedral	0°

In Figure 1, it is possible to visualize the Vahana vehicle simulation with the FLOWUnsteady applying the reformulated vortex particle method along with the particle strength Γ (Gamma). In this condition, the aircraft is performing the cruise phase.

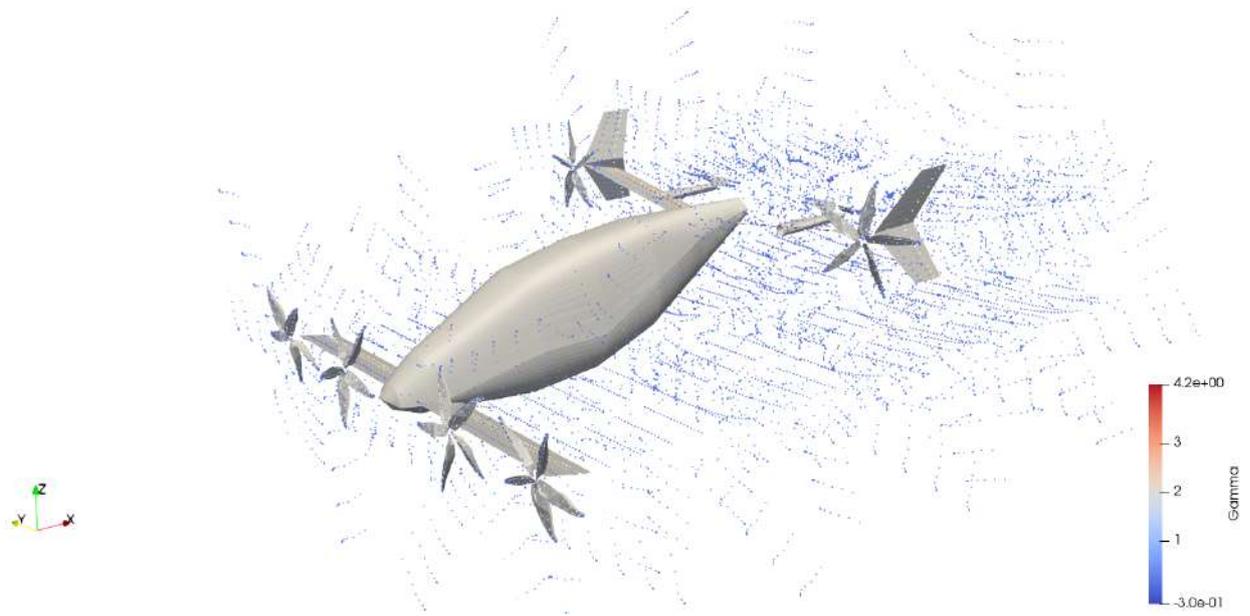


Figure 1. Vahana vehicle operation in cruise flight alongside particles generated by FLOWUnsteady.

Figures 2 and 3 depict the aerodynamic forces and coefficients of the aircraft during the flight phases. The evolution from the color red to blue in the figures is a representation of the evolution of the parameters through the steps of the simulated mission over time, which are takeoff-hover, cruise, and hover-landing, respectively. In Figure 2, the lift generated by an aircraft is distributed heavily over the span region, having as a result the structural components to be reinforced.

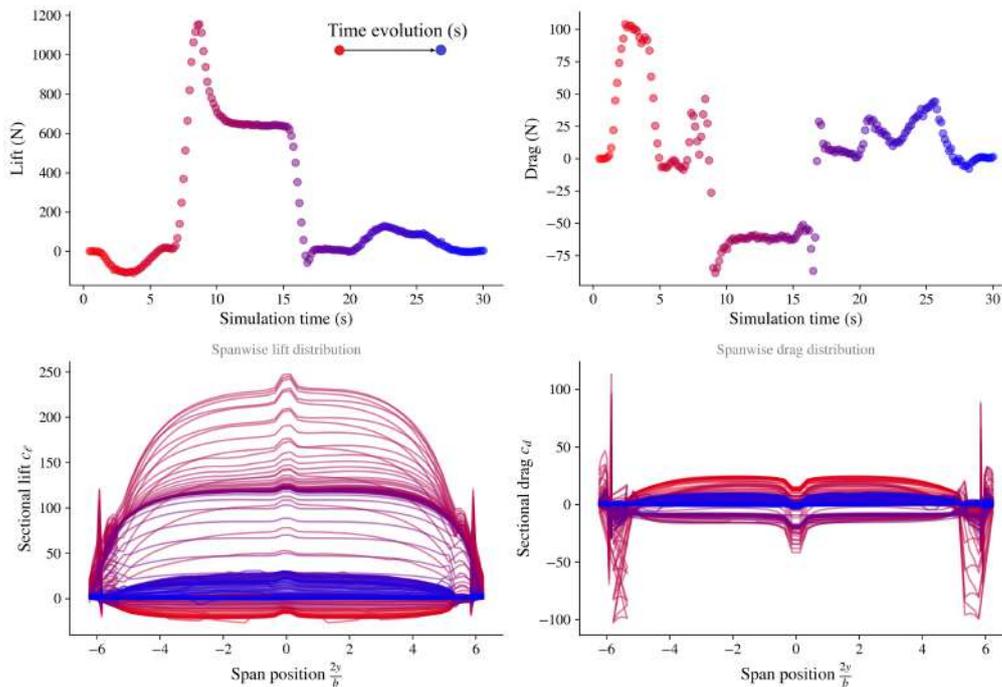


Figure 2. Aerodynamic forces and coefficients distributions along the main wing throughout the mission.

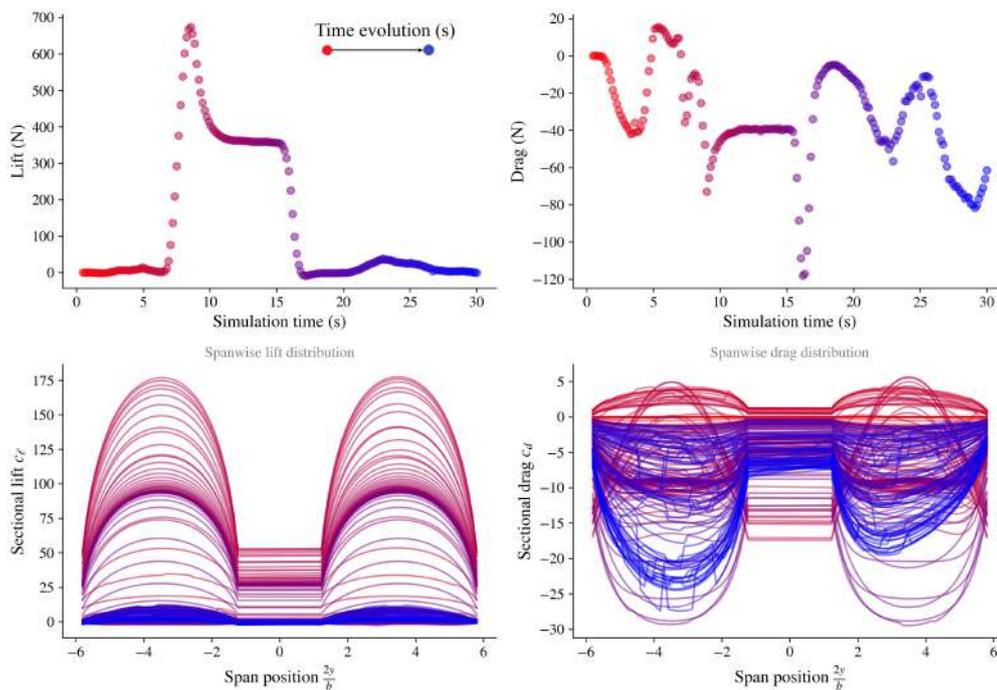


Figure 3. Aerodynamic forces and coefficients distributions along the tandem wing throughout the mission.

The evaluation of lift and drag values in the aircraft exhibited great results, indicating favorable aerodynamic performance. However, it is important to consider the trade-off between optimizing aerodynamic performance and ensuring passenger comfort. The positioning of the rotors in close proximity to the passengers leads to increased noise levels, necessitating the incorporation of soundproof elements. While these elements are essential for a comfortable and noise-controlled environment, their inclusion may impact the overall aircraft geometry and available space. Therefore, achieving the optimal balance between aerodynamic efficiency and passenger comfort becomes a crucial consideration, where careful design choices and compromises are made to provide both exceptional aerodynamic performance and a pleasant flying experience for passengers.

To address the challenge of balancing aerodynamic performance and passenger comfort, a solution was implemented by modifying the wings. Initially, the wing is increased by about 50% its original value, after it is sized back to its initial value with a taper ratio of 0.6. Finally, both modifications are added and evaluated. This modification aims to optimize the aircraft's aerodynamic characteristics while considering the noise and comfort requirements of the passengers. The revised Vahana vehicle structure, reflecting the resized wings, is presented in Figures 4, 5 and 6 during its cruise phase, showcasing the updated design.

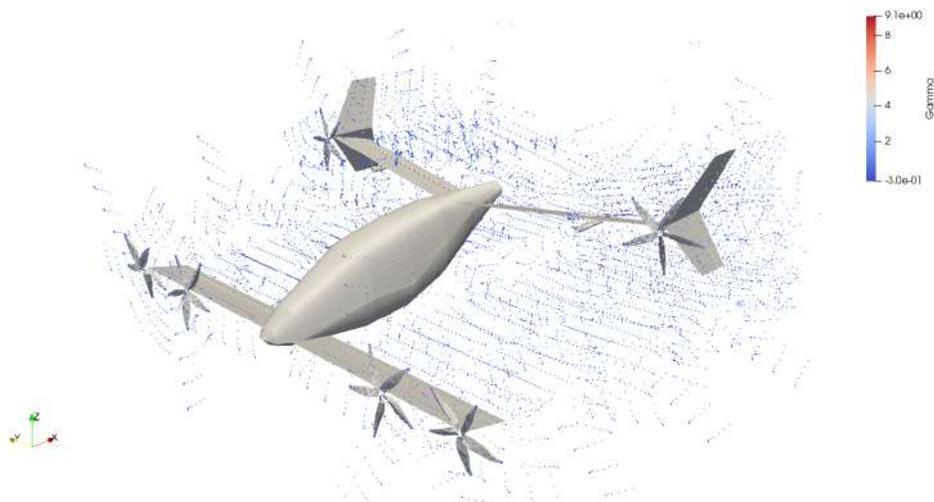


Figure 4. Vahana vehicle with wing increased by 50% operating in cruise with particles generated by FLOWUnsteady.

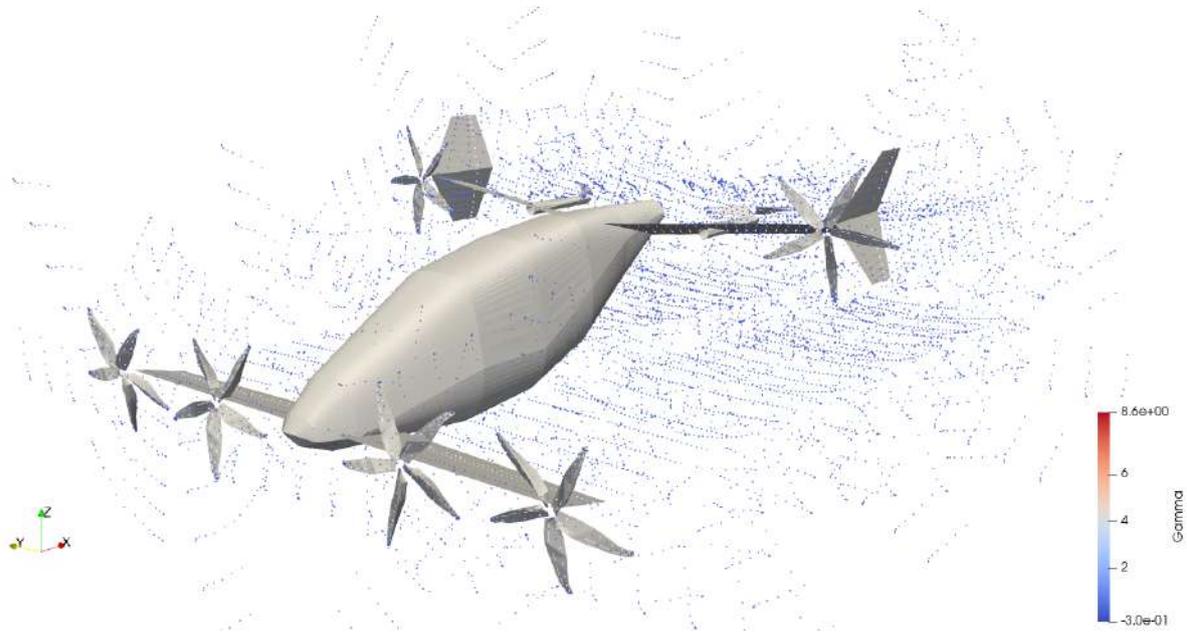


Figure 5. Vahana vehicle with taper ratio of 0.6 operating in cruise with particles generated by FLOWUnsteady.

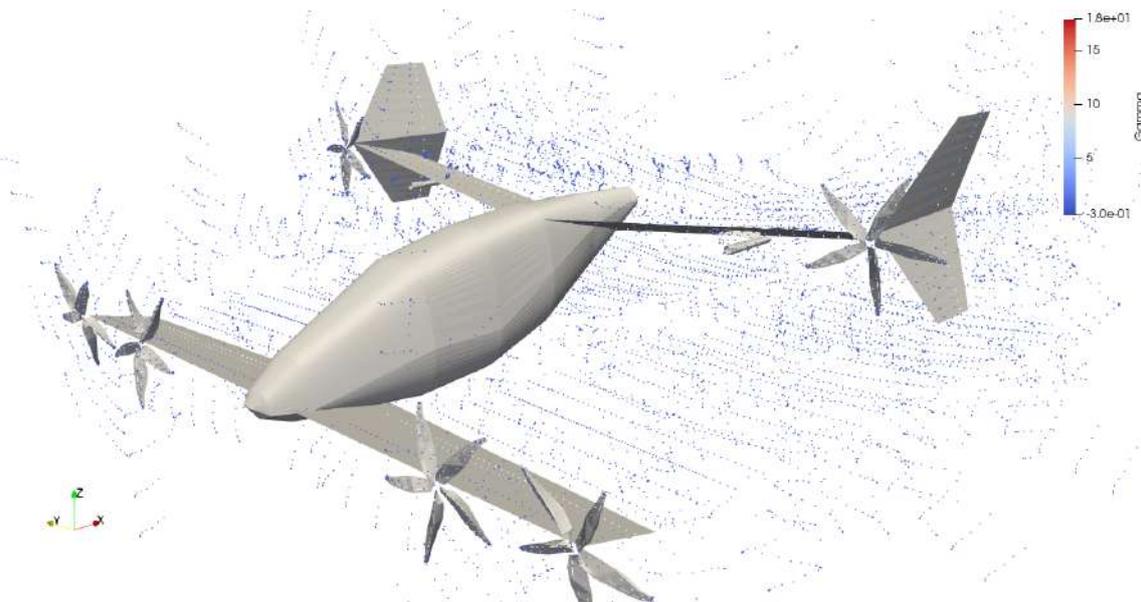


Figure 6. Vahana vehicle with wing increased by 50% and taper ratio of 0.6 operating in cruise with particles generated by FLOWUnsteady.

Further insights into the aircraft's performance can be observed in Figures 7 to 12, which illustrate the aerodynamic forces and coefficients experienced by the aircraft throughout different flight phases. These figures provide a comprehensive view of how the resized wings contribute to the overall aerodynamic behavior and efficiency of the eVTOL aircraft during takeoff, cruise, and landing phases. By analyzing these aerodynamic forces and coefficients, we can gain a deeper understanding of the aircraft's performance and its impact on mission objectives.

Upon increasing the wing size, it was observed that the lift generated by both the tandem and main wing experienced an increase. However, this increase in lift was accompanied by contrasting effects on the drag. The main wing exhibited an increase in drag, while the tandem wing experienced a decrease in drag.

This effect can be attributed to the altered lift distribution resulting from the increased wing size. The larger wing generates more lift due to the increased surface area, leading to improved aerodynamic performance. The distribution of lift along the wings is affected, with a greater proportion of lift being generated by the tandem wing compared to the main wing.

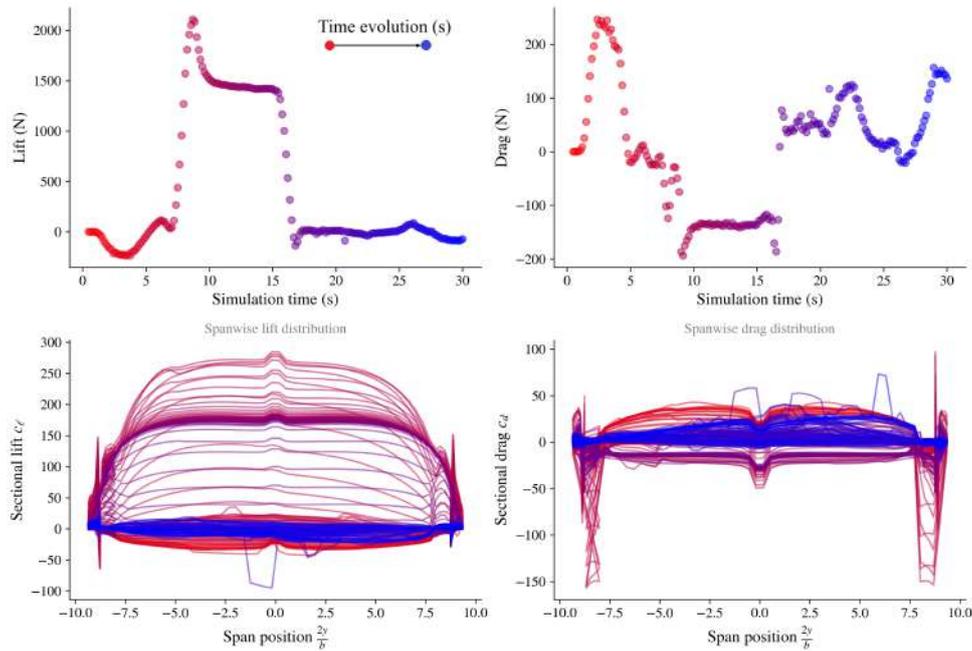


Figure 7. Aerodynamic forces and coefficients distributions along the main wing throughout the mission for wing modification.

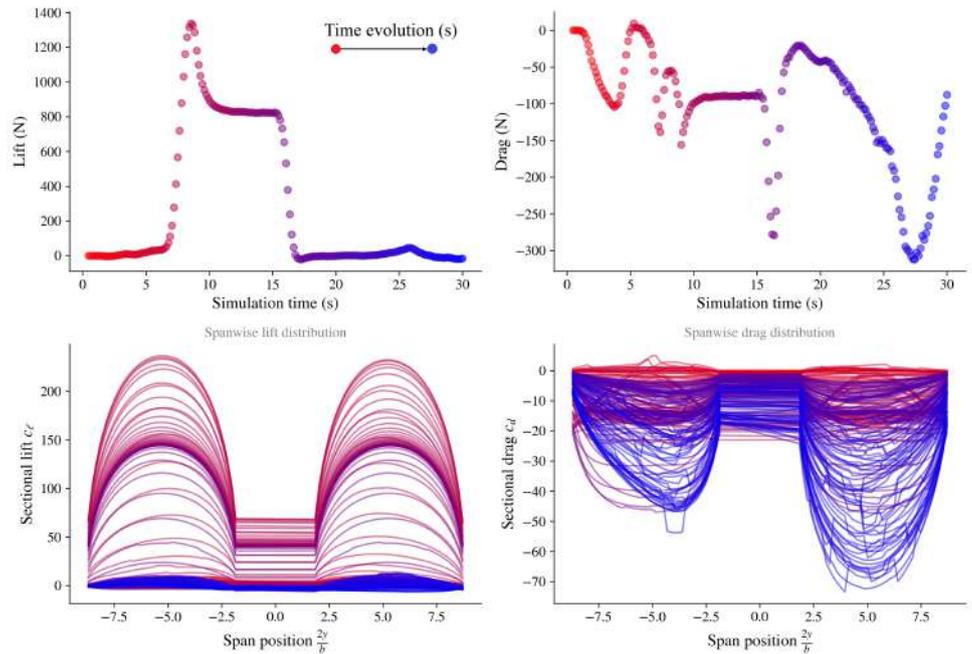


Figure 8. Aerodynamic forces and coefficients distributions along the tandem wing throughout the mission for wing modification.

By modifying the taper ratio of the wings, several notable differences were observed in comparison to the original and resized wings. In terms of lift, the modified taper ratio still yielded larger lift values than the original wing, although it was lower relative to the resized wing. Additionally, the modified taper ratio resulted in a spanwise lift distribution that was greater than both the original and resized configurations.

Regarding drag, the modified taper ratio exhibited lower drag values compared to the resized wing but similar to the original wing. The tandem wing, when subject to the modified taper ratio, displayed similar values for lift, drag, and spanwise lift distribution compared to the original wing. These values were lower than those observed in the resized wing, except for drag.

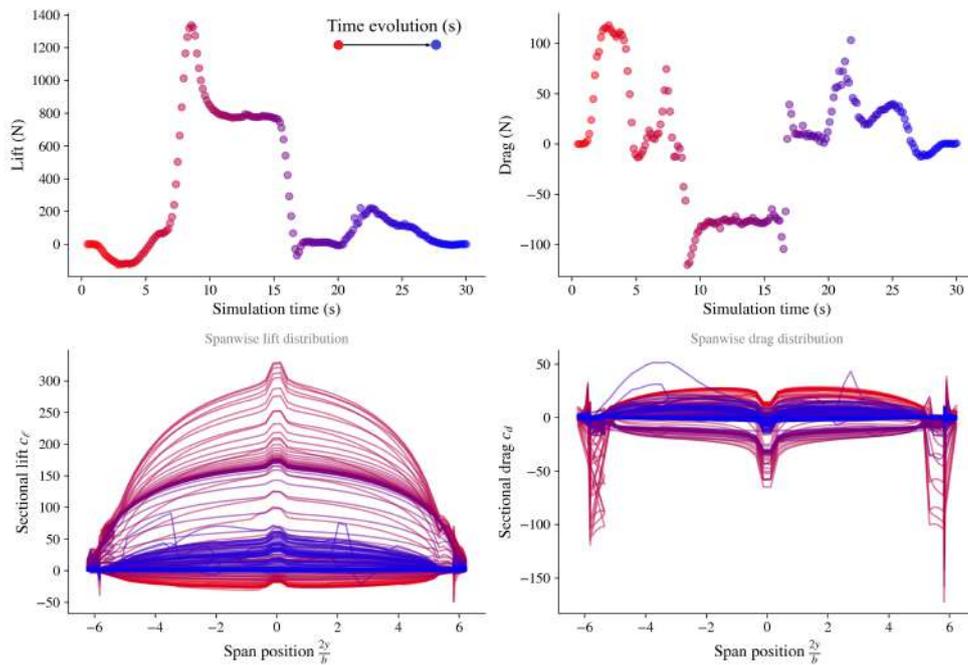


Figure 9. Aerodynamic forces and coefficients distributions along the main wing throughout the mission for taper ratio modification.

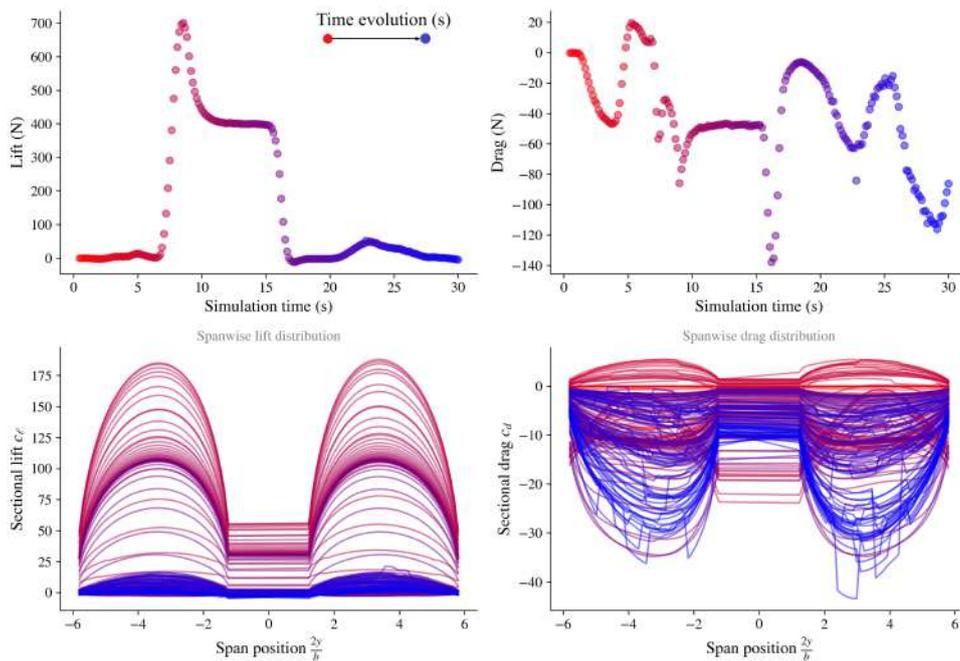


Figure 10. Aerodynamic forces and coefficients distributions along the tandem wing throughout the mission for taper ratio modification.

The altered taper ratio affected the lift distribution along the span of the wings, leading to increased spanwise lift distribution for the modified configuration. This, in turn, influenced the overall lift generated by the wing. The variation in drag can be attributed to the modified taper ratio's impact on the overall wing profile and resulting aerodynamic characteristics. The differences observed in the tandem wing's lift, drag, and spanwise lift distribution, which were similar to the original wing values, suggest that the modified taper ratio had a limited effect on these parameters for the tandem wing.

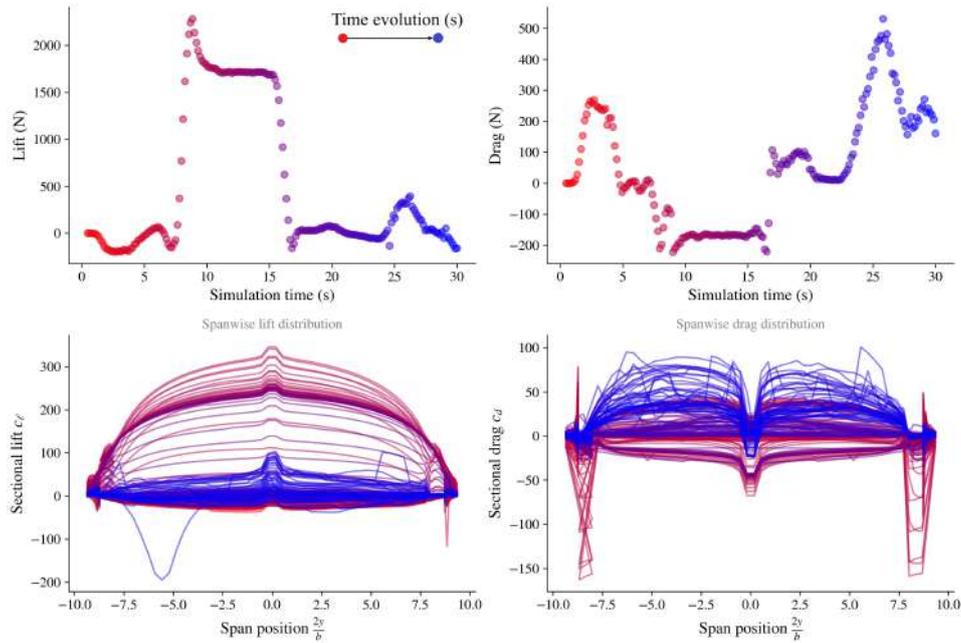


Figure 11. Aerodynamic forces and coefficients distributions along the main wing throughout the mission for wing and taper ratio modification.

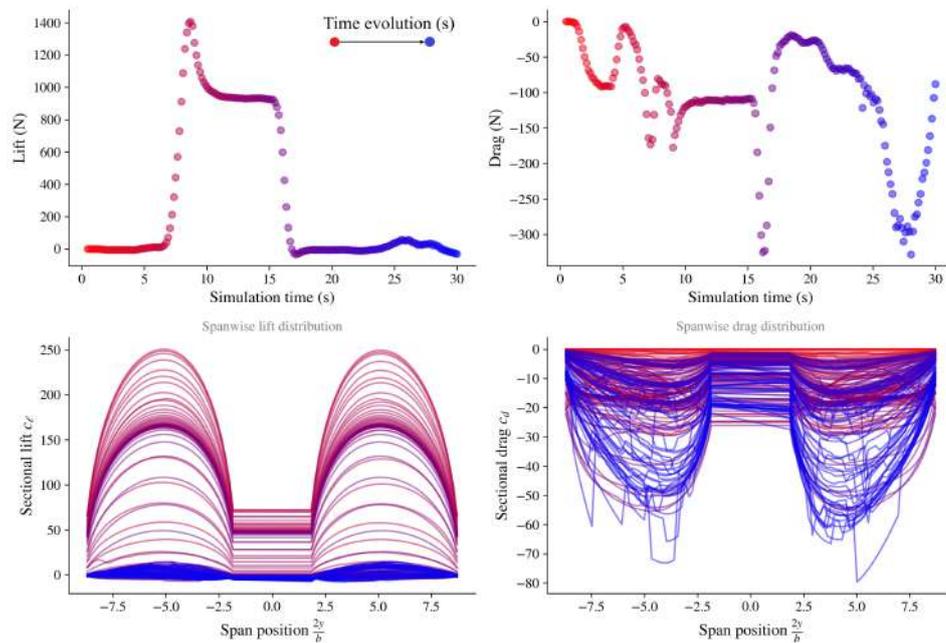


Figure 12. Aerodynamic forces and coefficients distributions along the tandem wing throughout the mission for wing and taper ratio modification.

When considering the resized and tapered wing configuration, a comparison of the results reveals interesting observations. Firstly, the combination of resizing and tapering the wing has resulted in the same lift as the resized wing. This indicates that the modifications have effectively maintained the lift-generating capabilities achieved through resizing. However, an increase in drag is observed compared to the resized wing, which suggests that the tapering of the wing has introduced additional drag-inducing effects. Additionally, the spanwise lift distribution remains the same as the resized wing. This implies that the modified wing configuration has successfully preserved the spanwise lift distribution achieved through resizing alone.

In terms of the tandem wing, it exhibits the same lift as the resized wing. This demonstrates that the resizing of the

tandem wing has been effective in maintaining lift performance. Moreover, the tandem wing configuration shows a greater spanwise lift distribution compared to both the original and resized wing configurations. This indicates an improvement in the aerodynamic characteristics of the tandem wing, allowing for enhanced lift distribution across its span. Interestingly, the drag of the tandem wing remains similar to that of the resized wing. This suggests that the modifications made to the tandem wing, such as resizing and tapering, have not significantly affected its drag characteristics, aligning it closely with the drag performance of the resized wing.

In summary, the combination of wing resizing and tapering has resulted in the same lift as the resized wing, accompanied by increased drag. The spanwise lift distribution has been preserved, indicating stability and control advantages. In the case of the tandem wing, similar lift to the resized wing is observed, along with a greater spanwise lift distribution and comparable drag performance. These findings highlight the intricate relationship between wing modifications and their impact on lift, drag, and spanwise lift distribution, which are crucial factors in achieving optimal aerodynamic performance for eVTOL aircraft.

The discussion so far has shed light on the quantitative outcomes of the wing modifications, with a focus on parameters such as lift, drag, and spanwise lift distribution. However, it is crucial to delve deeper into the underlying physical effects that drive these changes. When considering the resized and tapered wing configuration, it becomes evident that the maintenance of lift, despite an increase in drag, can be attributed to the retention of lift-generating capabilities through resizing. The added drag, on the other hand, can be traced back to the drag-inducing effects introduced by tapering. These effects can include changes in wingtip vortices, vortex shedding, and interference between adjacent wing sections, all of which contribute to the observed increase in drag. Additionally, the preservation of spanwise lift distribution suggests that the modifications maintained the flow patterns and pressure distributions achieved through resizing. This intricate interplay of physical phenomena exemplifies the need for a comprehensive understanding of the aerodynamic intricacies when modifying eVTOL wing structures.

4. CONCLUDING REMARKS

The modifications made to the wing structure of eVTOLs, specifically resizing and tapering, have demonstrated significant effects on their aerodynamics. Through the research conducted on the modified wing configurations, valuable insights have been gained regarding their impact on lift, drag, and spanwise lift distribution. The combination of resizing and tapering the wing produced the same lift as the resized wing but with increased drag. This finding highlights the importance of carefully balancing the trade-offs between lift and drag when implementing wing modifications. Furthermore, the results showed that the tandem wing, when resized, exhibited similar lift to the resized wing, a greater spanwise lift distribution, and comparable drag performance. This indicates that resizing had a more pronounced effect on the aerodynamics of the tandem wing compared to tapering.

The study has provided valuable insights into the effects of wing resizing and tapering on the aerodynamics of eVTOL aircraft. The physical effects responsible for the observed modifications are multifaceted. The combination of resizing and tapering influences lift, drag, and spanwise lift distribution by altering flow patterns, pressure distributions, and vortices around the wing. While resizing primarily impacts lift and spanwise lift distribution, tapering introduces additional drag-inducing effects. The findings emphasize the delicate balance between these factors and underscore the importance of optimizing wing modifications for eVTOLs.

Understanding the physical effects at play not only enhances the knowledge of eVTOL aerodynamics, but also lays the foundation for more efficient and effective wing design. By continually refining the understanding of these effects, a more equipped approach to improving eVTOL aircraft performance is developed, resulting in safer, more efficient aircraft and ultimately advancing the field of electric vertical takeoff and landing technology.

5. ACKNOWLEDGEMENTS

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