# A Standardized Mid-Fidelity Aerodynamic Comparison of Four Tiltrotor eVTOL Configurations Using SUAVE and VSPAero

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## Abstract

This study compares 4 representative tiltrotor platforms: Joby S4, Archer Midnight, Vertical Aerospace VX4, and Uber eCRM-001 in a typical UAM mission profile under standardized rotor and wing assumptions using an integrated OpenVSP-SUAVE-VSPAero framework. This work aims to isolate the influence of eVTOL configuration from proprietary optimizations on thrust generation and aerodynamic interaction by using standard wing airfoils and a consistent rotor design tool.

Vehicle geometries were modeled in OpenVSP. Rotor Operating conditions were obtained from the SUAVE conceptual design platform. Mid-fidelity aerodynamic analysis was done using VSPAero.

SUAVE results show a decrease in thrust requirements as the tilt angle decreases, with the most complexity occurring in the transition phase where lift shifts from rotors to wing. Archer Midnight and Vertical Aerospace VX4 show higher hover thrust requirements due to their high takeoff weights. They display localized thrust increase near mid transition due to numerical adjustments made to achieve solver convergence. Joby S4 and Uber eCRM-001 display a smoother thrust requirement trend. VSPAero simulations also show a gradual decrease in thrust from hover to cruise. Joby S4's continuously active rotor configuration maintained more stable performance than the hybrid configurations, which deactivate lift-only rotors after takeoff.

A comparative flight feasibility analysis was conducted, defined as the difference between VSPAero-predicted thrust and SUAVE-required thrust. This analysis reveals that Joby S4 maintains a positive margin across most flight phases. Archer Midnight and Vertical Aerospace VX4 show a marginal deficit in near-cruise phases. Uber eCRM-001 showed negative margins throughout the mission, indicating limited aerodynamic robustness under standardized assumptions.

Rotor-wing interactions enhances rotor thrust across all mission segments, while creating periodic pressure oscillations on the wings. Rotor-rotor interactions provide limited near-field benefits that dissipate in forward flight. The findings of this study highlight the significance of eVTOL configuration in determining performance and aerodynamic efficiency.

## Keywords

eVTOL; electric vertical take-off and landing aircraft; tiltrotor; transition aerodynamics; UAM; urban air mobility; VSPAero; SUAVE; OpenVSP; rotor–wing interaction.

## Introduction

Urban air mobility has taken the central stage in current aerospace research as a result of increasing demand for short-range, low-noise and sustainable transportation option in densely populated urban area. Among the readily available options, electric vertical takeoff and landing (eVTOL) vehicles are being eyed as possible answer to that question in both academia and industry, thanks to the recent developments in electric propulsion, battery and composite material technology. Tiltrotor eVTOLs stand out as one of the best candidate in the vast design space of eVTOLs given their maturity and readiness of technology. They offer better cruise efficiency than multicopters while providing vertical takeoff and landing capabilities, a key metric to be considered as a candidate for Urban Area Transportation. Proven tiltrotor concepts such as the V-22 Osprey and AW609 confirmed the feasibility of tilting rotors during transition and cruise. The learnings from those concepts continue to inform the current tiltrotor eVTOL designs [1].

Previous studies and demonstrator programs have highlighted the importance of aerodynamic interaction between the rotors and wing for the overall performance of eVTOLs. This interaction is even more important during the transition phase when the lift shifts from rotors to wings [2-4]. Earlier researches also showed that rotor wake impingement on wings can create unsteady loading, flow separation and loss of lift on the wings [5]. On top of that, distributed propulsion brings additional complexities such as wake contraction, rotor-rotor interference and shifting lift-sharing mechanism, all of which influence the thrust capability and control authority of an aircraft. Several studies tried to characterize these effects using CFD, wind tunnel testing and analytical modelling. But the results of these studies are often specific to an eVTOL configuration rather than universal, which makes cross vehicle comparison very difficult.

Another complication in cross vehicle comparison arises from lack of standardized baseline. Manufacturers optimize aircraft characteristics like rotor geometry, transition schedules and control laws to maximize their performance. As a result, comparing publicly available performance metrics becomes a comparison of how fine-tuned those aircrafts are, rather than comparison of purely geometric or aerodynamic factors. This denies the attempts by researchers to isolate configuration driven effects although configuration choices like rotor number and placement of rotors, rotor-wing spacing, tilt mechanisms, etc. has considerable effect on generated thrust and aerodynamic interaction even when rotor and wing parameters are held constant. Moreover, earlier researches have focused on single aircraft configurations or isolated aerodynamic phenomena without standardizing rotor and wing designs, which limits the ability to isolate purely configuration driven effects [6-8]. As a result, there remains a need for a systematic comparison under standardized design assumptions that reflects purely configuration driven aerodynamic effects.

Recent studies have used mid-fidelity tools like OpenVSP and VSPAero to demonstrate early stage aerodynamic trends in eVTOLs, especially during the transition phase. Usage of mid-fidelity tools enables the understanding of aerodynamic interaction between rotors and wing while being computationally efficient [9]. Also, conceptual design and optimization platforms like SUAVE and NDARC can predict integrated mission level performance, but their results require validation against physics based tools and experimental data [10]. These recent developments provide an opportunity to bridge conceptual sizing with physics based aerodynamic simulations through a connected workflow.

To address the aforementioned gaps in earlier researches, this study performs a standardized comparison of four representative tiltrotor eVTOLs, building on prior research and setting the stage for following methodology discussion. Our study uses standardized wing and rotor design framework across all eVTOL configurations. We designed the aircraft geometries in OpenVSP, calculated rotor sizing and flight conditions using SUAVE and validated results with VSPAero simulations across hover, transition, and cruise phases. This methodology aims to provide an apples-to-apples comparison of how vehicle configuration alone influences performance and aerodynamic interaction, independent of proprietary optimizations.

The rest of the paper is organized as follows: “Methodology” describes the selected aircraft parameters, mission profile and OpenVSP to SUAVE to VSPAero workflow. “Results and Discussion” presents the results from SUAVE sizing and VSPAero validation, their comparative analysis and interaction effects. “Conclusion and future work” discusses configuration based performance and interaction differences, concludes with key findings and presents direction for future research.

# Methodology

## *Selected Aircraft Models*

We selected 4 commercially relevant tiltrotor eVTOLS: Joby S4, Archer midnight, Vertical Aerospace VX4 and Uber eCRM-001 for comparison. They belong to the same vehicle class based on number of passengers and targeted mission profile, while representing distinct configuration choices.

Table 1 contains basic parameters of selected eVTOLs used in this study. To standardize the comparison, all vehicle wings were modeled with the same set of airfoils: NACA-4418 at the root, NACA-4415 at midspan and NACA-4412 at the tip.

Table 1. Basic geometric and weight parameters of selected eVTOLs.

| Parameter | Joby S4 | Archer Midnight | Vertical Aerospace VX4 | Uber eCRM-001 |
|---|---|---|---|---|
| No of Passengers | 5 (Pilot+4) | 5 (Pilot+4) | 5 (Pilot+4) | 5 (Pilot+4) |
| Takeoff Weight | 2404 kg | 3175 kg | 3500 kg | 2327 kg |
| Payload Weight | 350 kg | 456 kg | 450 kg | 410 kg |
| Total no. of rotors | 6 | 12 | 8 | 10 |
| No. of Lift-only rotors | 0 | 6 | 4 | 8 |
| Wingspan | 11.8 m | 14.6 m | 15 m | 11 m |
| Wing Area | 15.44 $m^2$ | 23.86 $m^2$ | 26.99 $m^2$ | 11.23 $m^2$ |
| Rotor Diameter | 1.9 m | 2 m | 2 m | 2.8 m, 2.5 m |

Rotor diameter, blade number and position of all rotors were selected based on published data. But rotor geometry including blade twist, chord distribution, airfoils, etc. were designed using SUAVE’s rotor sizing module, which employs blade element theory to generate a rotor design based on specified requirements. By standardizing these designs, this study isolates the impact of configuration on performance and aerodynamic interaction.

## *Mission Profile*

A standard mission profile simulating a typical urban area flight was selected for all vehicles. The mission includes a hover phase, a transition phase and a cruise phase so that the aircrafts can be judged in all application scenarios. Figure 1 shows the mission profile that each vehicle had to complete.

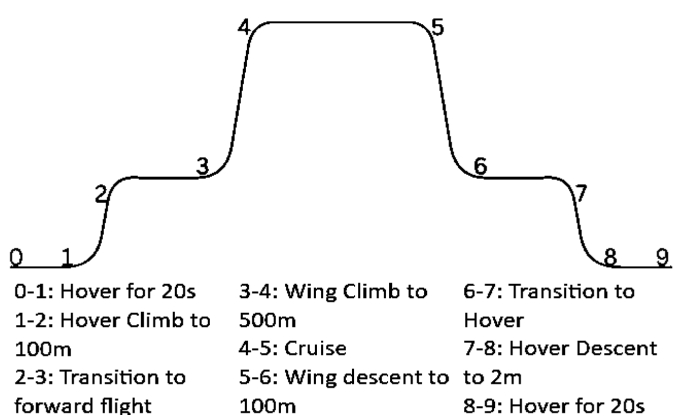

Figure 1. Mission profile for selected eVTOLs.

To ensure a fair comparison, all vehicles were evaluated under identical atmospheric conditions such as air density and altitude.

### *Simulation Workflow*

The simulation workflow consists of geometry creation, conceptual sizing and mid-fidelity aerodynamic validation as described below:

#### Geometry Creation in OpenVSP

This study used OpenVSP (Open Vehicle Sketch Pad) to construct 3d geometry of all selected eVTOLs. Wing, fuselage and tail geometries were constructed using corresponding primitives in OpenVSP according to published specifications. Rotor position, diameter and blade numbers were also matched with real aircrafts. Standard airfoils were applied to the wing sections. Rotor geometry was designed in SUAVE and then exported and attached to aircraft geometry.

#### Rotor Sizing Using SUAVE

We used SUAVE, an open source conceptual aircraft design tool that calculates rotor geometry, RPM, thrust and power requirements among other parameters, based on actuator disk momentum theory and blade element theory [11]. Thrust is computed using the ideal actuator disk theory:

$$T = 2\rho A v_i^2 \qquad (1)$$

where,

$T$ = thrust

$\rho$ = air density

$A$ = rotor disc area

$v_i$ = induced velocity

Rotor RPM is derived from:

$$\Omega = \sqrt{\frac{T}{k\rho A R^2}} \qquad (2)$$

where,

$\Omega$ = rotation per minute

$T$ = thrust

$k$ = thrust coefficient from blade-element theory

$\rho$ = air density

$A$ = rotor disc area

$R$ = rotor radius

Each aircraft geometry from OpenVSP were imported to SUAVE and then set up for selected mission profile. Simulations were then performed to obtain required thrust values to sustain flight in each mission segments. It's important to note that SUAVE accounts for forward flight corrections, calculating different flight conditions to match specific mission phase like hover, transition and cruise.

#### Mid-Fidelity Validation with VSPAero

The mid-fidelity validation simulation in this study was done using VSPAero. It uses a linear potential flow solver based on vortex lattice method (VLM) to compute aerodynamic loads on various lifting surfaces [12]. In VLM, each lifting surface is discretized into a lattice of quadrilateral panels. A bound vortex is placed along the quarter chord line of each panel and trailing edge vortices are shed downstream to form a wake that convects with the freestream velocity. This formulation transforms the classical lifting surface boundary condition such that the normal component of velocity at each control point vanishes creating a system of linear equations relating the unknown vortex strengths to the applied flow field.

For a given panel $i$, the local lift per unit span is obtained from the Kutta–Joukowski relation:

$$L_i = \rho_\infty V_\infty \Gamma_i \qquad (3)$$

where,

$L_i$ = local Lift

$\rho_\infty$= freestream density

$V_\infty$= freestream velocity magnitude

$\Gamma_i$= circulation strength of the bound vortex on panel $i$.

VSPAero uses a wake relaxation algorithm. The downstream vortices deform iteratively until a wake shape is formed, allowing the solver to capture induced drag, interference effects and rotor-wing coupling more precisely than fixed wake VLM solvers. This feature is of particular significance in tiltrotor eVTOL applications where rotor wakes impinge on the wing creating variable downwash distribution and affecting local lift and thrust.

Rotors were imported from SUAVE and modeled as rotating blades in VSPAero. For each aircraft, we performed a series of VSPAero simulations corresponding to rotor tilt angles from 90° (Hover) to 0° (cruise) in 10° increments, matching the mission segments in SUAVE. At each tilt angle, the aircraft geometry was modified to tilt the rotors to corresponding angle relative to the airframe. Freestream velocity, RPM and other simulation parameters were set to match those in the SUAVE simulations. The results from VSPAero simulations predict available thrust from the rotors in each mission segment. There are recent studies that show that VLM based solvers used alongside relaxed-wake algorithms predict moderately accurate results for low reynold's number eVTOL configurations [12].

#### Comparative Analysis

We then compared thrust values from SUAVE and VSPAero simulations across all mission segments to assess flight feasibility and highlight the influence of eVTOL configurations. VSPAero results were also used to visualize the aerodynamic interaction between rotors and wings.

## Results and Discussion

### *SUAVE Thrust Requirements*

Figure 2 shows the thrust requirements of each eVTOL as calculated by SUAVE. This reveals the thrust requirements of each eVTOL in each mission phase to sustain flight.

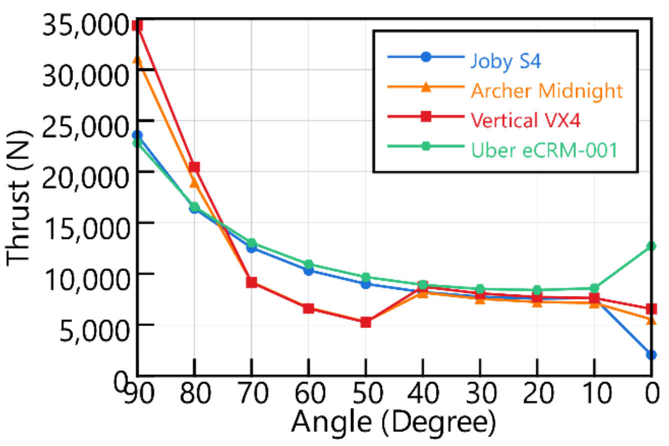


Figure 2. SUAVE thrust requirements of selected eVTOLs.

As shown in Figure 2, the thrust requirement values decrease monotonically with decreasing rotor tilt angle. This reflects the phenomena that lift is gradually shifted from rotors to wings as eVTOLs transition from hover to cruise.

Among the studied eVTOLs, Archer Midnight (31.1 kN) and Vertical Aerospace VX4 (34.3 kN) has the highest hover thrust requirements due to their high maximum takeoff weight. The thrust requirements of these eVTOLs fall sharply from 80° to 50° before showing a slight increase at 40° and then gradual decrease till 0°. It's important to mention that the increase between 50° and 40° is not because of any inherent aerodynamic factor. It occurs due to freestream velocity adjustment in SUAVE to ensure solver convergence. Higher forward velocity at lower tilt angles led to partial flow separation and loss of thrust in rotors, consequently failing SUAVE solver convergence. So, forward velocity was reduced in those mission segments, artificially decreasing the lift generated by wing and elevating the calculated thrust requirements. Similar phenomena have been documented in earlier studies of slowed rotor high advance ratio tests [13] and tiltrotor conversion experiments [14].

The graphs of Joby S4 and Uber eCRM-001 show a smoother decay in thrust requirement throughout the mission. Joby S4's six continuously active rotors maintain a relatively stable lift distribution, creating a gentle decrease in thrust requirement. Uber eCRM-001 shows similar trend to Joby S4, but has higher cruise thrust requirement due to induced drag from high number of rotors in its distributed lift configuration.

The similarities in thrust trend of Archer Midnight and Vertical VX4 represent their similarity in configuration. Both of them use hybrid tiltrotor design relying on a number of lift-only rotors during hover, which turn off during transition. On the other hand, Joby S4's true tiltrotor design uses a distributed continuously active rotors configuration that yields a gentler thrust trend. This variation of thrust trend highlights the effect of distinct configuration choices.

### *VSPAero Thrust Prediction*

VSPAero's VLM solver predicts thrust and other forces more accurately than analytical tools like SUAVE making use of 3D flow effects and wing-rotor interactions.

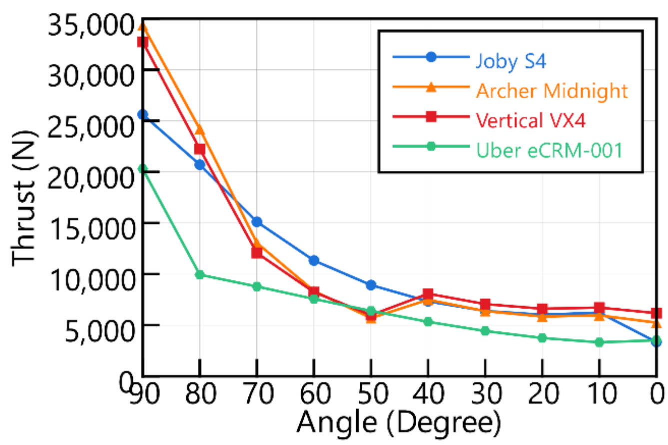


Figure 3. VSPAero thrust predictions of selected eVTOLs.

We can see in Figure 3, for all vehicles, available thrust decreases with decreasing tilt angle. This finding is consistent with other studies on tiltrotor and hybrid tiltrotor configurations.

During hover, Archer Midnight (34.3 kN) and Vertical VX4 (32.7 kN) generate the highest thrust, as a direct outcome of their hover-focused hybrid tiltrotor configuration. Joby S4 produces 25.6 kN of thrust while Uber eCRM-001 produces only 20.3kN of thrust with all the rotors active.

During transition phases of mission, all eVTOLs show a drop in available thrust. The drop is steeper for Archer Midnight and Vertical VX4 because the lift-only rotors deactivate after hover. The drop of available thrust after hover is similar for Uber eCRM-001, but maintains a comparatively gentler decay after the initial drop. Only Joby S4 shows a gradual drop of available thrust because it's the only configuration where all the rotors are active in all flight segments.

### *SUAVE vs VSPAero Comparison*

As a key metric of flight feasibility, we compared the required thrust for sustained flight calculated by SUAVE with the available thrust predicted by VSPAero using the following formula:

$$\Delta T = T_1 - T_2 \quad (4)$$

where,

$\Delta T$ = Thrust Margin

$T_1$ = VSPAero Thrust

$T_2$ = SUAVE Thrust,

Earlier research proved this margin based approach significant for transition performance assessment [15]. A positive $\Delta T$ value shows that the eVTOL can generate enough thrust to sustain flight in standardized conditions, while a negative value means the inability to sustain flight.

At hover, Joby S4 and Archer Midnight show a positive $\Delta T$ value, +2.0 kN and +3.2 kN respectively. Vertical VX4 shows a marginal deficit of -1.6 kN, and Uber eCRM-001 shows a deficit of -2.5 kN. The deficit of Vertical VX4 is likely due to the high maximum takeoff weight, which makes the configuration unable to achieve hover at the standardized setting.

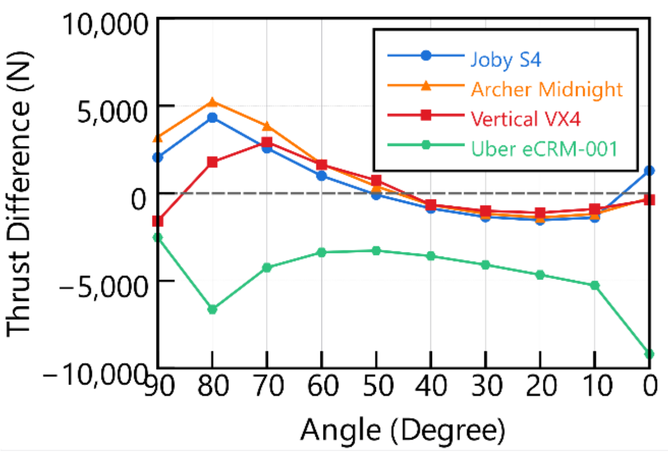

Figure 4. Difference between the SUAVE thrust requirement and the VSPAero thrust predictions of selected eVTOLs

In transition, all eVTOLs show a positive margin down to 50° tilt angle except Uber eCRM-001, demonstrating their ability to sustain flight in those mission segments in standardized conditions. In near cruise mission segments, all eVTOLs show negative $\Delta T$ values. At cruise, only Joby S4 shows a positive margin, while Archer Midnight and Vertical VX4 show a marginal deficit. Uber eCRM-001 shows a large deficit in all mission segments, especially during cruise (-9.18 kN) and 80° tilt (-6.6 kN).

This comparison shows the significance of configuration choices in maintaining flight feasibility. Joby S4 with a true tiltrotor design and continuously active rotors outperforms other hybrid tiltrotor configurations like Archer Midnight, Vertical VX4, and Uber eCRM-001 in standardized conditions.

## *Rotor–Wing Interaction*

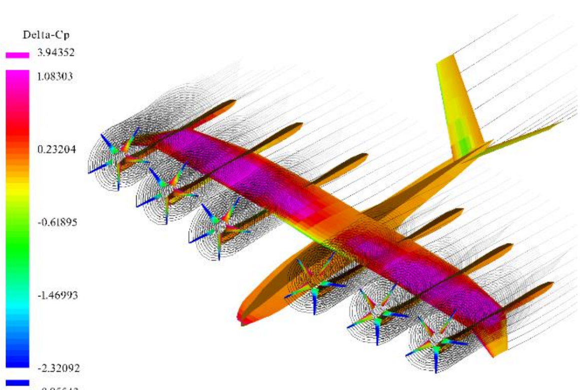

Figure 5. VSPAero visualization of rotor-wing interaction of Archer Midnight at 50° tilt angle.

We analyzed the influence of rotor-wing interaction by comparing rotor thrust in the presence and absence of the wing. All eVTOLs in all mission segments showed an increase in thrust when the wing was present. We can see in Figure 5, flow from the rotors passing over the wing creates a lower pressure zone on top of the wing. This increased the rotor thrust by 2-7% compared to the thrust when the wing is absent. This finding is consistent with earlier studies [16, 17].

Another prominent aspect of rotor-wing interaction that was observed in our study is the generation of periodic unsteady pressure fluctuations on wing surfaces as the rotor wake impinges on the wing. This observation corresponds to Blade-Vortex Interaction (BVI) phenomena, a well-known phenomenon in rotorcraft aerodynamics. We observed that as the rotor wake travels downstream, it creates alternating high and low pressure zones on the wing surfaces. These oscillations were momentary and gradually dampened with time. The severity of the oscillations and damping time varied in different configurations and mission profiles.

During hover, with the rotors at vertical position and wings creating no lift, aerodynamic interaction is hardly observable in any eVTOL configurations. This happens because, at hover, negligible flow exists over wing surfaces since the rotor wakes miss the wings almost entirely.

Archer Midnight and Vertical VX4 experienced the maximum fluctuations at a 40° tilt angle. At 60°, all eVTOLs except Uber eCRM-001 faced a sustained but less severe oscillation. Also, in configurations with multiple rotors per wing side (Archer Midnight, Vertical VX4), wakes from different rotors created constructive and destructive interference. This sometimes cancelled each other out, sometimes multiplied the oscillation amplitude, resulting in highly unsteady behaviour. Uber eCRM-001 was the least affected configuration in terms of rotor-wing interaction due to its rotors sharing a very small cross section with the wing.

At cruise, with the rotors aligned with the flight direction, wing-rotor interaction varies with configuration. Joby S4 experiences moderate initial oscillations, which dampen quickly. For Archer Midnight and Vertical VX4, the oscillations are more severe than those of Joby S4 due to constructive interference of multiple rotor wakes. Uber eCRM-001 is the least affected, even during the cruise.

These observations show that the placement of rotors relative to the wing in different configurations can improve thrust generation. Furthermore, the wake impingement on wings can create transient instability and could result in momentary loss of control.

## *Rotor–Rotor Interaction*

Observation of VSPAero flowfields reveals that rotor wakes create a modest constructive effect. This is more relevant in near-field regions. As seen in Figure 6, rotor wakes don’t overlap physically, but their induced velocity fields interact to slightly enhance thrust. The observed phenomena are most prevalent at low advance ratios in all selected eVTOLs.

These wake-induced benefits disappear rapidly as the rotors tilt forward and the eVTOL gains higher forward velocity. This observation is consistent with earlier studies [16, 17].

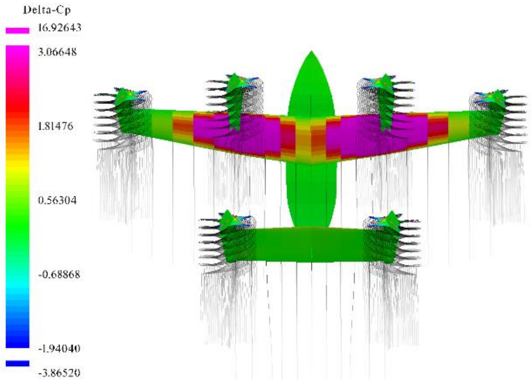

Figure 6. VSPAero visualization of rotor-rotor interaction of Joby S4 at 90° tilt angle (hover).

## Conclusion and Future Work

We presented an integrated OpenVSP-SUAVE-VSPAero framework in this study for standardized mid-fidelity comparison of tiltrotor eVTOLs. We applied this framework to compare 4 representative tiltrotor platforms: Joby S4, Archer Midnight, Vertical Aerospace VX4, and Uber eCRM-001 in a typical UAM mission profile under standardized rotor and wing assumptions. The results of this study quantified how vehicle configuration influences flight feasibility and aerodynamic interaction in different phases of flight.

The results of this study provide several key findings. Among the studied eVTOLs, the true tiltrotor configuration of Joby S4 stands out as the best one based on several factors. Joby S4 maintained a positive thrust margin in most mission segments. In terms of aerodynamic interaction, Joby S4's design outperforms the other eVTOLs except Uber eCRM-001. This establishes Joby S4's distributed lift configuration with continuously active rotors as best among the studied eVTOLs.

Archer Midnight and Vertical Aerospace VX4 show great hover capability but fall behind in terms of performance when the lift-only rotors are phased out in later mission segments. Also, they suffer more from aerodynamic interaction because of their high number of rotors per wing side. Both of these hover-optimized designs show that there is more to consider than just hover performance when developing an eVTOL platform.

Uber eCRM-001's configuration is the least prone to aerodynamic interaction effects, but it fails to achieve a positive thrust margin in any mission segment. This explains why this design never progressed beyond the conceptual phase.

Our study shows that rotor-wing interactions provide a benefit by enhancing rotor thrust across all mission segments. However, the same interaction also creates periodic pressure oscillations on the wings, which might lead to momentary loss of control and inefficiencies.

The findings of this study emphasize the significance of rotor placement, the number of rotors, and continuity in maximizing flight feasibility and beneficial aerodynamic interaction, even in the absence of proprietary optimizations.

The standardized OpenVSP-SUAVE-VSPAero framework used in this study serves as an effective mid-fidelity evaluation framework. It is capable of providing meaningful insights into configuration-driven performance differences while being computationally more efficient than high-fidelity CFD. This framework allows apples-to-apples comparisons between eVTOL concepts, revealing underlying design merits and limitations that are obscured by the proprietary optimizations.

The findings of this study can be further investigated in future studies by including high-fidelity CFD simulations and flight dynamics analyses. Future studies can explore beyond the scope of the Vortex Lattice Method to capture unsteady, viscous, and turbulence induced effects.

Furthermore, a more consistent evaluation of eVTOL configurations can be done by integrating mission-level energy and efficiency metrics. Expanding the comparison to a broader number of eVTOL concepts will further inform future design of tiltrotor eVTOL platforms.

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## Declaration of AI-Assisted Technologies

During the preparation of this work, the author(s) used ChatGPT and Claude AI in order to debug simulation errors. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.