

Energy Optimization Strategies for Automatic Tiltrotor eVTOL Aircraft

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I. Introduction

The advent of electric Vertical Take-off and Landing (eVTOL) aircraft has coincided with advancements in batteries and electric motors technologies, enabling these aircraft to operate in urban environments with reduced noise [1]. Among the dominant eVTOL configurations, Vectored-Thrust and Lift+Cruise designs have gained prominence due to their superior cruise efficiency and extended range when compared to multicopter architectures [2]. These two designs leverage a combination of lift and thrust mechanisms to optimize energy usage during different flight phases, making them attractive options for urban air mobility applications. However, these configurations necessitate transition flight, which introduces challenges in unsteady aerodynamics, conversion strategy and control allocation [3-4]. Two types of controllers are employed in transition flight: manual piloted flight control systems and automatic control systems. Traditional Vectored-Thrust aircraft like XV-15 have relied on manual transition control strategies. However, in the emerging field of Advanced Air Mobility, automatic control systems have shown promise [5]. This paper focuses on a specific type of Vectored-Thrust configuration, Aston Martin Volante Vision [6], exploring its minimum energy dynamics for automatic control system.

An automatic conversion control system is the preferred choice, especially given the use of flight-naïve pilots, to ensure the commercial viability of the future personal air mobility market [7]. Flight-naïve pilots are expected to have more limited training requirements, akin to those qualifying for a private pilot license [8]. This highlights the rationale behind the necessity for implementing an automatic conversion system relieving the need for pilots to manage arbitrary pitch attitudes and airspeeds manually from the expected high workload demanding. In the existing eVTOL literature, particularly regarding information published by Original Equipment Manufacturers, Joby Aviation emerges as the singular entity offering comprehensive design concepts for an automatic conversion flight control system. Joby

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Aviation has proposed a scheduled angle of attack approach for the automation of accelerating and decelerating transition phases [9]. Under straight level flight condition, constant acceleration and deceleration schedules have been explored and optimized to minimize power consumption by maximizing angle of attack. Nevertheless, the correlation between transition flight along the minimum power path and achieving the global minimum energy expenditure within the regime of the whole mission scenarios remains a subject of investigation, due to the different acceleration strategies in the transition phase will lead to different energy consumption.

A low level of battery energy density currently stands as a predominant barrier to optimal eVTOL performance. Several optimization formulations for the conversion scenarios have addressed this challenge by minimizing the cost function of energy [10]. The Airbus Vahana model has contributed to the discourse by providing a minimum energy speed profile under specific time constraints, although it has omitted pitch dynamics and transition trajectory, without considering possible passenger discomfort due to normal load [11]. Another study [12] also used the Vahana model and delved into minimum-energy-optimized conversion flight. The conversion flight demonstrated a constant acceleration and climb, but both pitch dynamics and reconversion flight were absent. It was found that most research on minimum-energy-oriented automatic conversion systems primarily focused on transition phases and lacked detailed consideration of pitch dynamics during these flight phases.

However, a typical mission scenario for eVTOL aircraft encompasses not only conversion and reconversion flights but also vertical takeoff and landing, climb and descend, and cruise flight phases. It is important to acknowledge that the power and time expended during conversion and reconversion flight phases influence the overall performance of the cruise flight. The primary objective of this paper is to develop a comprehensive tilt schedule for conversion and reconversion processes, with the aim of minimizing energy consumption across all operational scenarios. The paper begins by providing information on the aircraft model. It then introduces candidate tilt schedules to examine potential minimum energy transition strategies. Finally, through an optimization process, the paper seeks to identify the tilt schedule configuration that offers the most efficient energy performance across the entire mission diagram.

II. Aircraft Modelling Description

A. Overview of Aircraft Modelling

The Aston Martin Volante Vision Concept model adopted in this paper is illustrated in Fig. 1.



Fig. 1 Aston Martin Volante Vision concept.

The aircraft model is a Vectored-Thrust configuration, with transitions facilitated by the front two tilting rotor pairs. Detailed modeling of this aircraft can be found in Ref. [13]. The following section provides only a brief overview of the aerodynamic characteristics and power calculations for this model. Firstly, the Athena Vortex Lattice [14] method is used to analyze aerodynamic characteristics and derive the aerodynamic derivatives. The lift coefficient C_L , drag coefficient C_D , and pitching moment coefficient C_M are modelled as follows based on the reference [15]:

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}q + C_{L_\eta}\eta \quad (1)$$

$$C_D = C_{D_0} + KC_L^2 + C_{D_\eta}\eta \quad (2)$$

$$C_M = C_{M_0} + C_{M_\alpha}\alpha + C_{M_q}q + C_{M_\eta}\eta \quad (3)$$

where C_{L_0} is the zero-lift coefficient, an C_{L_α} is the lift curve slope. C_{L_q} and C_{L_η} are lift coefficients due to pitch rate (q) and elevon deflection (η), respectively. C_{D_0} is the zero-lift drag coefficient, K is the lift-induced drag coefficient factor, C_{D_η} is the drag coefficient due to η , C_{M_0} is the zero-lift moment pitch coefficient, C_{M_α} is the pitching moment slope. C_{M_q} and C_{M_η} are pitch moment coefficients due to q and η , respectively.

Secondly, the blade element momentum theory solver called QPROP [16] was used to calculate the performance of the rotor thrust, along with semi-empirical corrections for coaxial rotors [17]. The power coefficient C_P is based on the study [18] and modelled as:

$$C_P = \kappa\lambda_i C_T + \lambda_c C_{Z_e} + \mu C_{x_w} + \frac{1}{8}\sigma C_{D_{mean}}(1 + 4.65\mu^2 + F_P) \quad (4)$$

where κ is the induced power factor, λ_i is the induced inflow ratio, C_T is the thrust coefficient, λ_c is the climb flow ratio, C_{z_e} is the propulsive force coefficient in the earth-axis z direction, μ is the advance ratio, C_{x_w} is the propulsive force coefficient in the wind-axis x direction, σ is the rotor solidity, $C_{D_{mean}}$ is the mean rotor blade drag coefficient, and F_p is the axial profile power factor represented in Eq. (5) as a function of axial flow ratio μ_z [19].

$$\sqrt{1 + \mu_z^2}(1 + 2.5\mu_z^2) + 1.5\mu_z^4 \ln \left[\left(1 + \sqrt{1 + \mu_z^2}\right) / \mu_z \right] \quad (5)$$

B. Transition Dynamics Formulation

The typical mission profile of the Volante encompasses vertical take-off, conversion, climb, cruise, descent, landing, and a potential reserve mission. The critical transition phases of conversion and reconversion flights, the focus of this paper, is introduced here, with an emphasis on analyzing global minimum energy dynamics across all operational scenarios.

The development of the minimum energy automatic control relies on a good level of understanding of the conversion dynamics flight. Figure 2 illustrates the operational conversion corridor of the Volante Vision, derived from straight level flight trim conditions exploration [20]. The lower boundary in Fig. 2 is delineated by the wing stall region, while the upper boundary is defined by power and structural limitations. The structural model is not absent, but a limit was imposed as the blade structure limit at an advance ratio of 0.45 [21].

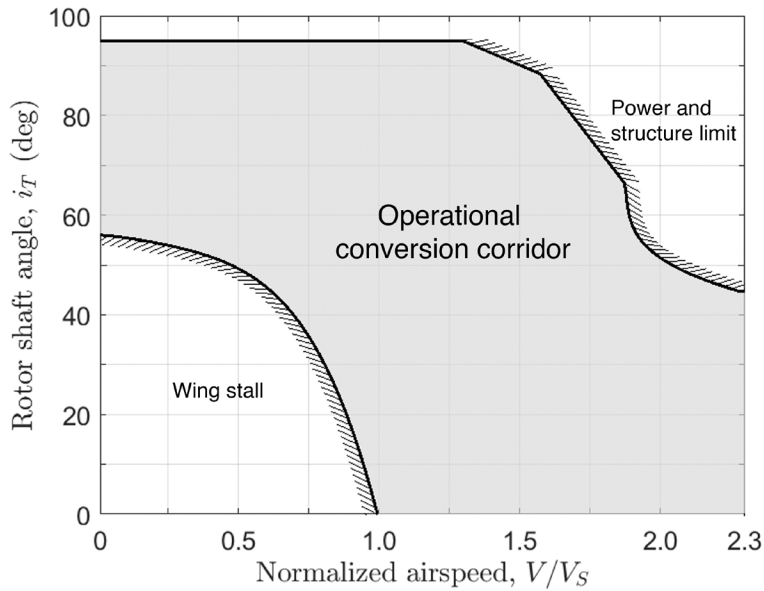


Fig. 2 Volante Vision operational conversion corridor.

The conversion and deceleration reconversion dynamics of the Volante transition are described by Eqs. (6) to (8) with the reference systems are defined in Fig. 3:

$$ma_{x_w} = 2T_{TR} \cos(\alpha + i_T) - T_{DR} \sin \alpha - D - W \sin \gamma \quad (6)$$

$$ma_{z_e} = 2T_{TR} \sin(\theta + i_T) + T_{DR} \cos \theta + L \cos \gamma - D \sin \gamma - W \quad (7)$$

$$I_{yy} \dot{q} = 2T_{TR} (\sin i_T x_{TR} + \cos i_T z_{TR}) + T_{DR} x_{DR} + M \quad (8)$$

where m is the aircraft mass, a_{x_w} is the horizontal wind-axis acceleration, T_{TR} is the tilt rotor thrust, α is the angle of attack, i_T is the tilt rotor shaft angle, T_{DR} is the ducted rotor thrust, D is the aerodynamic drag, W is the aircraft weight, γ is the flight path angle, a_{z_e} earth-axis vertical acceleration, θ is the pitch attitude, I_{yy} is the pitch inertia, $\dot{q}$ is the pitch acceleration, x is the horizontal moment arm from c.g., z is the vertical moment arm from c.g., and M is the aerodynamic pitching moment.

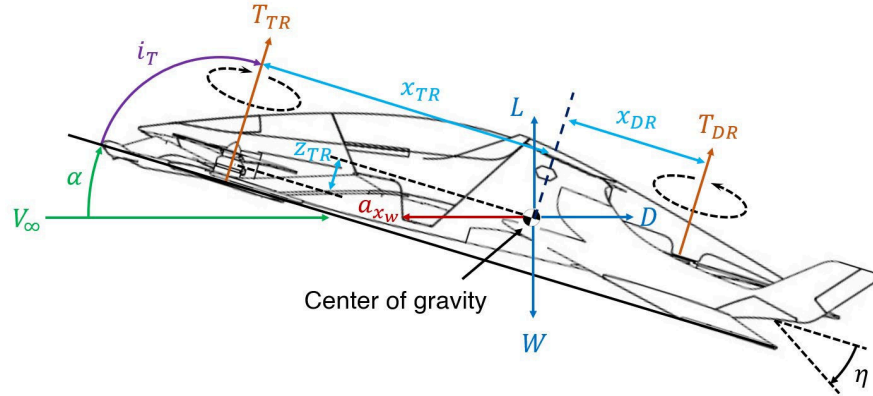


Fig. 3 Control effector, angle and vector definitions at straight-level flight.

The theoretical foundations underlying these equations are established through the following rationale. Firstly, straight-level acceleration and deceleration are expected to perform conversion and reconversion flights, respectively. Hence, a_{z_e} , γ , $\dot{q}$, and q are all set to zero, as illustrated in Fig. 3, and thus the equations can be further simplified. η is set to counteract the pitching moment produced by T_{DR} , which becomes redundant in the wingborne flight phase. If acceleration is determined under these conditions, aerodynamic lift, drag forces, and pitching moment become functions of α in conversion domain. Thus, three equations become solvable with three unknown variables – T_{TR} , T_{DR} , and α . With a constraint of -5 to 5 deg on θ for passenger comfort [22], Eqs. (6) through (8) with varying acceleration,

airspeed, and rotor shaft angle was solved to analyze minimum energy performance during conversion acceleration and reversion deceleration phases.

III. Minimum Energy Conversion and Reversion Analysis

This section focuses on analyzing the minimum energy tilt schedule design during its mode transition phases, examining both conversion and reversion flights. The study introduces a cubic tilt schedule equation and investigates three different tilt schedules with varying shaft angles to understand their effects on energy consumption and transition time. Through detailed analysis of acceleration, deceleration, pitch attitudes and thrust vectoring, the section aims to determine the optimal tilt schedule strategy for each transition phase.

A. Minimum Energy Tilt Schedule

The energy consumption during conversion and reversion flights is described in Eq. (9).

$$E = \int_{t_1}^{t_2} P dt = \int_{V_1}^{V_2} \frac{P}{a} dV \quad (9)$$

in which E is the energy consumption, t_1 is the initial time, t_2 is the terminal time, V_1 is the initial airspeed, V_2 is the terminal airspeed, P is the power consumption during transition flights. This suggests that minimum energy consumption occurs when the minimum power flight condition aligns with maximum acceleration during conversion flight. If power and acceleration can be expressed in the conversion domain (i.e., rotor shaft angle and airspeed domain), energy becomes a function of airspeed and shaft angle. Furthermore, if rotor shaft angle depends on airspeed, energy can be estimated based on airspeed. To facilitate this minimum energy approach, we introduce the following cubic tilt schedule, where k , c_1 and c_2 are coefficients in Eq. (10).

$$i_T(V) = k(V - c_1)^3 + c_2 \quad (10)$$

There are three unknown coefficients in the cubic tilt schedule. However, two known conditions are given during conversion and reversion. The initial airspeed is the hover speed at 5 kt with a rotor shaft angle of 85 deg, which will be 95 deg in reversion for this study. The terminal airspeed is the cruise speed in wingborne flight, which is

121 kt (i.e., $V \in [V_l, V_2] \subset \mathbb{R}$ and $i_T(V_l)$ and $i_T(V_2)$ are known). Hence, the cubic tilt schedule becomes a function of one tilt schedule free variable, k by defining tilt schedule coefficients c_1 and c_2 in Eq. (11).

$$\begin{aligned} c_1 &= \frac{V_2 + V_1}{2} - \sqrt{-\frac{(V_2 - V_1)^2}{12} + \frac{i_T(V_2) - i_T(V_1)}{3k(V_2 - V_1)}} \\ c_2 &= -k(V_1 - c_1)^3 + i_T(V_1) \end{aligned} \quad (11)$$

In further conversion and reconversion analysis, three different tilt schedules are investigated with varying k . One represents the case when RPM control mode is more effective, the second reaches the lower boundary as quickly as possible, and the third one is an intermediate value.

B. Conversion Flight Analysis with Tilt Schedule

Figure 4 illustrates the largest applicable acceleration on the conversion domain with varying tilt schedules. The acceleration performance dynamics were obtained from 0.005 g to 0.2 g with an interval of 0.005g through Eqs. (6) to (8) in conversion domain. The highest acceleration was selected at every single airspeed and shaft angle point according to the minimum energy mechanism introduced in Eq. (9). Three tilt schedules are taken into consideration based on the level of dominance of power-lift effort, and large tilt shaft angle in Fig. 4. Furthermore, acceleration and pitch attitude variation along tilt schedules is provided in Fig. 5 over the time domain.

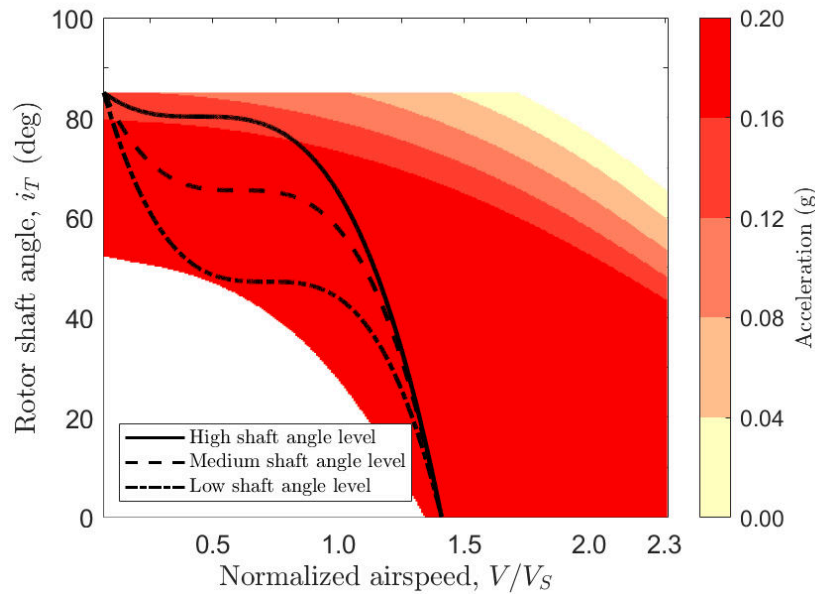


Fig. 4 Largest applicable acceleration conditions against three level of shaft angle tilt schedules.

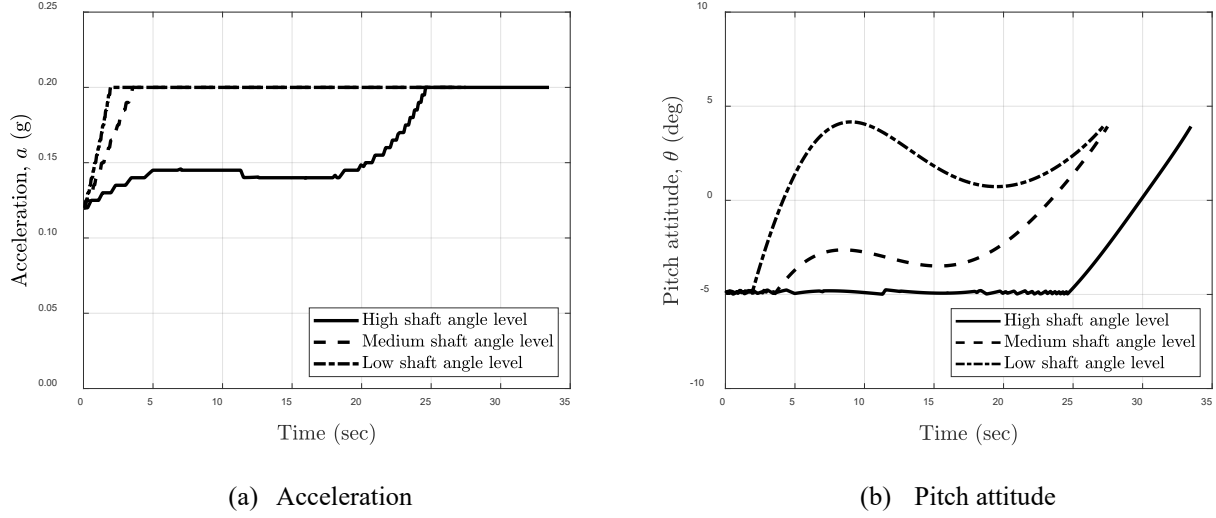


Fig. 5 Acceleration and pitch attitude profile against three level of shaft angle tilt schedules.

The high shaft angle tilt schedule ($k = -0.00151$) mostly experiences negative pitch attitude and was not able to perform the maximum acceleration available under pitch attitude constraints. However, the low shaft angle line ($k = -0.00235$) turns into a positive attitude in the quickest manner. Non-smooth points in pitch attitude plots occurred due to interpolation between minimum grid points. Using pitch attitude information in Fig. 5, pitch rate and pitch angular acceleration were newly taken into account in the acceleration dynamics analysis through Eqs. from (6) to (8), but the pitch attitude constraints already prevented excessive pitch maneuver and did not result in a significant change in the given acceleration performance contour trend. The conversion results with tilt schedules are provided in Table 1. Time information was derived from dV/a where V is discretized.

Table 1 Conversion tilt schedule characteristics.

Shaft angle level	Low	Medium	High
Time	27.2 sec	27.5 sec	33.9 sec
Max tilt rate	-11.8 deg/sec	-11.8 deg/sec	-11.8 deg/sec
Energy	2.4 kWh	2.7 kWh	3.4 kWh

All three tilt schedules recorded a maximum tilt rate of -11.8 deg per second just prior to achieving the cruise configuration. It should be noted that tilt schedules may not perform such tilt rate due to actuator limitations, even though the autonomous conversion system is assumed to comply with these schedules. The line with the low level of the shaft angle contribution achieved the minimum energy (2.4 kWh) and showed the quickest conversion (27.2 sec). This is due to the fact that the highest level of acceleration was maintained for the majority of the conversion period.

By enhancing lift through a positive aircraft angle of attack, the ducted rotor thrust demand for powered lift and pitch balance was effectively reduced and substituted with aerodynamic lift and elevon deflection, thereby achieving the rapid optimization of the process led closely to the minimum power consumption. However, the high shaft angle configuration failed to achieve the maximum acceleration range owing to the substantial rotor shaft angle prior to reaching cruise speed. This limitation resulted in increased energy consumption, amounting to 3.4 kWh, and prolonged the conversion time to 33.9 sec. According to the tilt schedule function outlined in Eq. (10), the low shaft angle tilt schedule emerges as the tilt schedule associated with minimum energy consumption.

C. Reconversion Flight Analysis with Tilt Schedule

Figure 6 illustrates the largest applicable deceleration on the reconversion domain with varying tilt schedules. The deceleration performance dynamics were obtained from -0.005 g to -0.18 g with an interval of -0.005 g in conversion domain through Eqs. (6) to (8). The highest deceleration was selected on the reconversion domain according to the minimum energy strategy. Additionally, Figure 7 illustrates the deceleration profile along the three tilt schedules in the time domain.

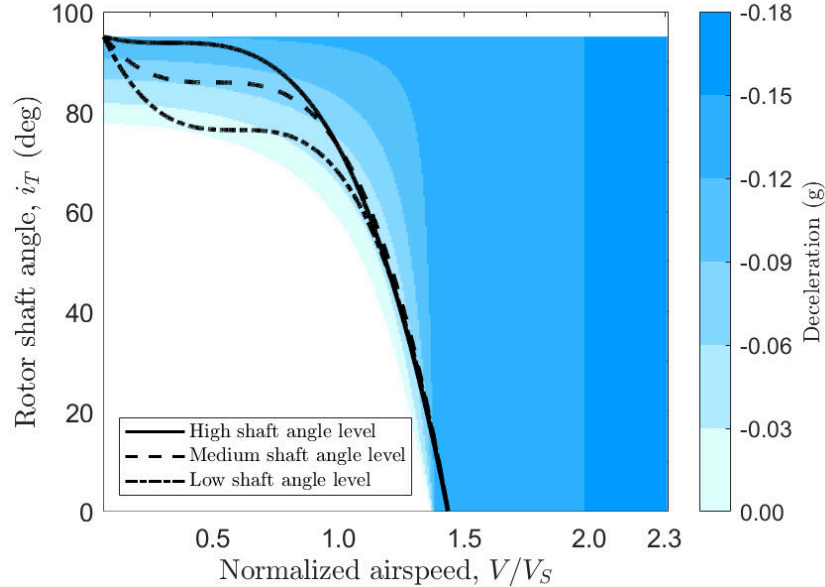


Fig. 6. Largest deceleration applicable conditions against three level of shaft angle tilt schedules.

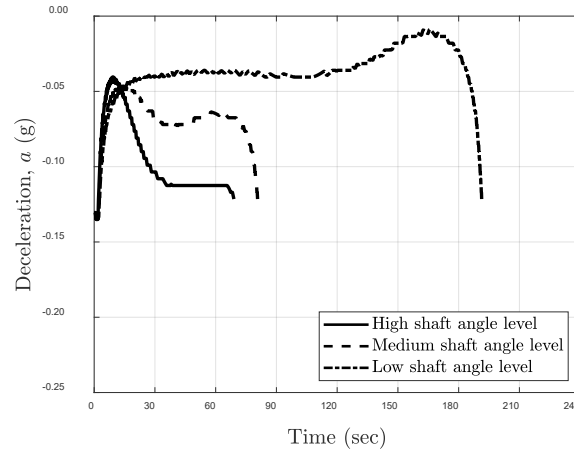


Fig. 7 Deceleration profile against three level of shaft angle tilt schedules.

Contrary to the varying pitch attitudes observed during acceleration phases, the pitch attitude in all tilt schedules during reconversion remains constant at 5 deg, adhering to the maximum pitch attitude constraint. This consistency underscores that the greatest deceleration is achieved by increasing the angle of attack, thereby elevating induced drag and enhancing the aircraft's deceleration capabilities. Specifically, the high shaft angle tilt schedule ($k = -0.00116$) managed to achieve the maximal deceleration available in the low-speed region. This effectiveness stems from the thrust being directed slightly rearward due to the positive pitch attitude and rotor shaft angle, allowing the horizontal components of thrust to contribute significantly to deceleration. However, this deceleration strategy was not feasible for the low shaft angle line ($k = -0.00215$). The reconversion results with tilt schedules are provided in Table 2.

Table 2 Reconversion tilt schedule characteristics.

Shaft angle level	Low	Medium	High
Time	191.4 sec	80.7 sec	69.0 sec
Max tilt rate	8.7 deg/sec	8.7 deg/sec	8.7 deg/sec
Energy	11.2 kWh	3.7 kWh	2.8 kWh

Overall, the reconversion process is more time-consuming than acceleration due to the absence of a direct control source for deceleration, unlike during the conversion phase. All tilt schedules reached their maximum tilt rate of 8.7 deg/sec immediately following the cruise configuration. The high shaft angle line achieved minimal energy consumption, using only 2.8 kWh, and exhibited the fastest reconversion time at 69.0 seconds. Conversely, the low shaft angle line consumed the most energy, up to 11.2 kWh, and recorded the slowest reconversion time of 191.4 seconds, a significant contrast to the acceleration phase. Since all tilt schedules exhibit nearly identical drag forces at

each airspeed, it is determined that the positioning of thrust vectoring is crucial for energy conservation. In this context, it is observed that swiftly increasing the rotor shaft angle to achieve the hover configuration effectively transforms the drag force from an impediment to a benefit.

IV. Global Optimization Analysis

It remains unclear whether these minimum energy tilt schedules during conversion and reversion equate to the global minimum energy across all operational scenarios, including climb, cruise, and descent. In this section, a nonlinear optimization analysis is employed, encompassing a variety of tilt schedules, to minimize energy consumption across the entire mission profile. Initially, the power consumption during takeoff and landing is considered constant, because climb and descend speeds are fixed based on the operational diagram assumed; therefore, they are excluded from the optimization objective. Conversion power P_1 and reversion power P_5 are a function of k that were defined in the previous section. Climb power P_2 and descend power P_4 is a function of vertical speed. Finally, cruise power P_3 is a function of time over the cruise range. The objective of minimizing energy consumption along with the optimization constraints is formalized in Eq. (12). Two equality conditions are established to reflect the operational range and altitude scenarios. Additionally, inequality conditions are defined to ensure optimization within the maximum battery capacity of 273 kWh.

$$\min J = \sum_{i=1}^5 \int_{t_{i-1}}^{t_i} P_i dt \quad (12)$$

in which the tilt schedule parameters, k for P_1 and P_5 , vertical speed, V_z for P_2 and P_4 and cruise time, t for P_3 within the boundary:

$$\begin{bmatrix} k_1 \\ V_{z2} \\ t_3 \\ V_{z3} \\ k_5 \end{bmatrix} = \begin{bmatrix} -0.00235 & -0.00151 \\ 0 \text{ fpm} & 1000 \text{ fpm} \\ 0 \text{ min} & 80 \text{ min} \\ -800 \text{ fpm} & 0 \text{ fpm} \\ -0.00215 & -0.00116 \end{bmatrix}$$

satisfying with the constraint conditions,

- horizontal travel distance, $X = 162 \text{ nmi}$
- vertical travel distance, $Z = 1500 \text{ ft}$
- total energy consumption, $E < E_{\text{battery}} = 273 \text{ kWh}$

The results of nonlinear optimization are contained in Table 3.

Table 3 Nonlinear optimization results.

	Optimization parameter	Energy	Time
Conversion	−0.00235	2.4 kWh	0.5 min
Climb	1000 fpm	4.8 kWh	1.5 min
Cruise	75.7 min	160.0 kWh	75.7 min
Descend	545 fpm	3.6 kWh	2.8 min
Reconversion	−0.00116	2.8 kWh	1.2 min
Total	-	173.6 kWh	81.7 min

The conversion and reconversion tilt schedules have been identified as minimizing energy consumption in the preceding section also aligned with the global minimum energy strategy. Regarding climb performance, the optimal climb rate, V_y , occurs at a pitch attitude of 12.2 deg and an angle of attack of 6.3 deg, resulting in minimum energy consumption. This is attributed to the decrease in angle of attack at higher climb speeds, reducing the thrust required to overcome drag at the same airspeed. However, it is important to acknowledge that since the primary focus was on conversion and reconversion flights, the atmospheric model was not incorporated into this optimization study. Consequently, climb speed will vary depending on the altitude, given the presence of atmospheric model in the optimization process. For descent operation phase, a slight negative pitch attitude was introduced to enhance passenger comfort, with the optimized descent rate being 545 fpm. Considering that cruise flight in optimization is dependent upon other flight phases, the optimization results highlight climb, cruise, and descent as critical parameters since achieving local minimum energy in conversion, and reconversion ultimately leads to the global minimum energy.

V. Conclusions

This study examines tilt schedules across various operational scenarios to understand their impact on energy use in the Aston Martin Volante aircraft. Using a nonlinear optimization approach, we identified configurations that minimize energy expenditure during conversion and reconversion phases, aligning with an overall strategy of global energy reduction. The analysis spans the entire mission profile revealing that certain tilt schedules can significantly cut energy use by optimizing rotor shaft angles for aerodynamic efficiency. These findings enhance the framework for energy management in eVTOL operations and offer insights for future aircraft design and control system improvements, supporting more energy-efficient practices crucial for eVTOL urban viability. The study also opens

potential for adaptive control systems that dynamically adjust energy use based on real-time operational data and conditions.

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