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Tilt Angle Control Planning for eVTOL using Trim Anlaysis

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Abstract

This study proposed a tilt angle control planning methodology for eVTOL tiltrotor vehicle strictly considering the requirements of UAM flight operations in a transition flight. Previous studies often disregard human-oriented comfortability in transition and consider pitching behaviors as usual UAVs. Our approach adopts trim analysis for the generation of a tilt angle control plan in the elaboration of the angle of attack schedule upon flight speed. As a result, the study helps to generate the tilt angle control plan by the tile angle. This work contributes to the development of UAM vehicle control and operations for passenger comfortability and safety.

1. Introduction

The emergence of electric Vertical Takeoff and Landing (eVTOL) aircraft has had a significant impact on the modern aviation industry. Conventional aircraft rely on fossil fuels, leading to air pollution, while eVTOLs utilize electric propulsion systems, causing no atmospheric pollution. Moreover, traditional aircraft have been used for short or long-distance transportation based on the characteristics of fixed-wing or rotary-wing configurations. However, eVTOLs can selectively utilize the characteristics of both fixed-wing and rotary-wing aircraft, depending on their configuration. The main eVTOL configurations include multirotor, lift and cruise, and tiltrotor. eVTOLs possess multiple rotors in the vertical direction, which increases stability and enables vertical takeoff and landing. However, multirotor designs have limitations in long-distance flights due to the absence of wings. lift and cruise designs incorporate wings and separate horizontal rotors, allowing for long-distance flights. tiltrotor have wings and the ability to change the thrust direction of the rotors instead of utilizing separate horizontal rotors, resulting in a challenging configuration.

tiltrotor can perform vertical takeoff and landing like rotary-wing aircraft when the thrust direction is vertical and high-speed cruising like fixed-wing aircraft when the thrust direction is horizontal. They also have the characteristic of the transition flight, where the rotor's thrust direction changes, causing significant changes in the aircraft's shape and flight characteristics, making it a complex and challenging phase. The tilt corridor, which serves as a reference metric for the stable transition flight of tiltrotor aircraft, can be derived through high-fidelity performance data and trim analysis of the aircraft. The tilt corridor represents the minimum and maximum flight speeds within the operational range of the tiltrotor aircraft based on the tilt angle. However, the tilt corridor alone does not provide a conclusive decision regarding rotor tilt angle control as it only indicates the area where the aircraft can perform the stable transition flight.

In a previous study[1, 2], a comprehensive trim analysis methodology was developed to identify the tilt corridor and establish tilt angle control strategies. In this study, we expand on the previous research by integrating the consideration of the human-oriented Urban Air Mobility (UAM) operation and maintaining a constant angle of attack. This is done to minimize changes in pitch angle during the transition flight for smooth transition, improving passenger comfortability and flight stability. This study focuses on tilt angle control planning of a real-world boxed-wing eVTOL vehicle for UAM scaled model, called `KP-2` as seen in Figure 1, currently under development at Konkuk Aerospace Design Airworthiness Institute (KADA), Konkuk University, Seoul, South Korea. Beyond that, the *contributions* of this research are in the following aspects:

- Adoption of trim analysis for a real-world boxed wing eVTOL aircraft in the tilting phase taken into account a schedule of the angle of attack.
- Proposal of methodologies for generating tilt corridor and tilt angle control planning.

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- Comprehensive generation and analyses of various flight dynamics factors during the transition phase depending on tilt angle including (i) tilt angle control plan, (ii) angle of attack, (iii) trim control values such as thrust and control surface deflection angle.

  Based on the analysis results, the finding of this study is:

- If the use of the angle of attack schedule is not considered, the vehicle transits to cruise mode with negative pitching angles during the whole transition period. Therefore, to obtain a smooth and comfortable transition, the adoption of a reasonable schedule for changing the attitude is required in UAM operations.
- With the adoption of angle of attack scheduling, the behavior of the transition flight changes from pitching down in helicopter mode as usual to tilting only rotors without changing the attitude in order to reach sufficient flight aerodynamics.

The remaining content is organized as follows. In Section 2, a literature review is presented on the modeling of eVTOL tiltrotor vehicles and the control of transition flight. Section 3 introduces the trim analysis method with the modeling process of the eVTOL tiltrotor vehicle, and the proposed approach for deriving tilt corridors and tilt angle control planning are explained. Section 4 presents the results and analysis of the generated tilt corridors and tilt angle control plan. The paper concludes in Section 5.

Figure 1: Real-World Scaled Model of KP-2

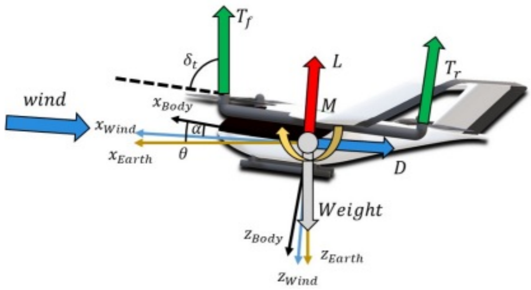

Figure 2: Body Frame and Coordinates

2. Related Work

The increasing demand for urban air mobility has generated significant interest in eVTOL (electric Vertical Take-off and Landing) technology, highlighting the importance of understanding their aerodynamics for safe and efficient operation. Wind tunnel testing, a commonly used method in the aerospace industry, has been employed to study the aerodynamics of eVTOL vehicles, as demonstrated in [3]. This testing allows for the measurement of lift, drag, and other aerodynamic characteristics by observing the airflow around the vehicle. It also helps validate computational fluid dynamics simulations and identify areas for vehicle design improvement. Wind tunnel tests can be conducted in low-speed or high-speed tunnels depending on the desired flow conditions. Another approach to understanding eVTOL aerodynamics is empirical modeling, as discussed in [4]. This involves fitting mathematical models to experimental data obtained from wind tunnel tests, flight tests, or other sources. Empirical models provide a simplified representation of the vehicle's aerodynamic behavior, allowing for real-time control, performance prediction, and optimization studies. Various eVTOL designs, including tiltrotor, tilt-wing, and multi-rotor configurations, have been evaluated for their aerodynamic performance using wind tunnel testing and empirical modeling techniques, as shown in [5,6]. These studies have focused on optimizing design parameters such as wing sweep, tilt angle, and propeller size and placement to enhance aerodynamic efficiency, as described in [7,8]. Wind tunnel testing and empirical modeling play crucial roles in optimizing eVTOL designs to ensure their safe and efficient operation as eVTOL technology continues to advance.

The planning and optimization of tilt angle in tiltrotor eVTOL vehicles have been significant areas of focus in aerospace engineering. Trim analysis, as discussed in [9], has been utilized to assess stability and control during both vertical and horizontal flight phases. It is also valuable for analyzing the aircraft's behavior under disturbing conditions such as wind gusts, turbulence, or control malfunctions, and for designing control systems that ensure a safe and stable flight, as explained in [10,11]. The trim analysis is a conventional and essential method for examining aircraft stability

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and control, particularly for tiltrotor eVTOL vehicles, enabling the design of control systems that guarantee efficient and stable flight under different conditions.

Optimizing the tilt angle is crucial in the design of eVTOL vehicles to determine energy-efficient trajectories throughout various flight phases. Researchers have explored several parameters, including wing loading and angle of attack, and have applied constraints such as acceleration, stall, and propeller flow augmentation to strike a balance between energy efficiency and passenger safety and comfort, as mentioned in [12]. Gradient-based optimization techniques, as discussed in [13], have proven to be fast and accurate in optimizing the tilt angle of eVTOLs, including tandem tilt-wing aircraft. Although there is extensive literature on tilt angle optimization for eVTOLs, further research is necessary to address the challenges associated with passenger safety and comfort as eVTOLs become increasingly integrated into urban air mobility systems.

3. Methodology

3.1 Vehicle Modeling

Vehicle configuration: In this paper, we study the method of deriving tilt angle control plans for stable and efficient transition flight of tiltrotor vehicle. The vehicle used in this research is a scaled model of an eVTOL tiltrotor with a boxed wing and V-tail control surfaces, designed by the Konkuk Aerospace Design Airworthiness Institute, Konkuk University, Seoul, South Korea. The propulsion system consists of four electric motors and propellers. Similar to a typical quadrotor drone, it is symmetrically arranged in the front-back and left-right directions. The two front motors can change direction through servo motors, while the two rear motors are fixed in the vertical direction of the aircraft. Therefore, this aircraft is a tiltrotor vehicle capable of only changing the direction of certain propulsion systems. The vehicle's specification of the longitudinal direction can see in Table 1.

Table 1: Longitudinal Direction Specifications

Components	Value	Unit	Symbol
Wing Area	0.8	m^2	S
Mass	14.28	kg	m
Wing Mean Aerodynamics Chord Length	0.32	m	$\bar{c}$
Body X Axis Distance between Front Propeller and CG	0.4997	m	l_{X_f}
Body Z Axis Distance between Front Propeller and CG	0.1512	m	l_{Z_f}
Body X Axis Distance between Rear Propeller and CG	0.4997	m	l_{X_r}
Tilt Angle Range	0 to 90	deg	δ_t
V-tail Control Surface Deflection Angle Range	-23 to 23	deg	δ_v

To achieve stable transition flight, precise trim analysis for the longitudinal axis at steady-state level flight is required to determine the tilt corridor, and tilt angle control plans are established within the tilt corridor. The trim analysis requires mathematical modeling of the forces and moments acting on the aircraft. Therefore, in this section, we will derive the mathematical modeling process and its results.

Gravity: Generally, the physical factors affecting an aircraft include the gravity component, propulsion component, and aerodynamics component. The gravity component is the force acting in the direction from the center of gravity of the aircraft to the center of the Earth, defined in the Earth Inertia Frame. The acting force can be expressed as the product of gravity acceleration (g) and the mass of the aircraft (m) as shown in Equation 1.

$$\begin{cases} F_{X_{E_G}} = 0 \\ F_{Z_{E_G}} = mg \\ M_{Y_{E_G}} = 0 \end{cases} \tag{1}$$

Propulsion: The propulsion component consists of the thrust and torque generated by the electric motor propellers in the eVTOL aircraft, acting on the axis of the propeller's center. In this paper, we did not consider the torque generated by the electric motor propellers as we performed trim analysis for the longitudinal axis. The electric propulsion system of the eVTOL tiltrotor uses a BLDC (Brushless Direct Current) motor and a fixed-pitch propeller. The BLDC motor used is the KDE5215XF-435 model manufactured by KDE Direct, and the propeller used is the PJN propeller with a diameter of 15in and a pitch of 7in manufactured by XOAR. The performance of the propulsion system, including thrust and torque, was measured using the subsonic wind tunnel facility at Konkuk University, with

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data collected at wind speeds from $0m/s$ to $20m/s$ at intervals of $5m/s$. The test focused on measuring the performance of a single propulsion system. To consider the variation in propeller performance limitation with flight speed, only the maximum thrust corresponding to each inflow speed was utilized. For the inflow speed range beyond $20m/s$, which was difficult to measure due to the limitations of the wind tunnel test, cubic splines were used to predict the performance variation.

Aerodynamics: The aerodynamic longitudinal forces and moments include lift, drag, and pitching moment. The aerodynamic coefficients of the aircraft consist of the static stability coefficient, control stability coefficient, and dynamic stability coefficient. Since this research focused on trim analysis for steady-state level flight, the dynamic stability coefficient was not considered. The static stability coefficient varies with the angle of attack of the aircraft, so one-dimensional data was constructed based on the angle of attack. The control stability coefficient varies not only with the angle of attack but also with the control surface deflection angle, so two-dimensional data was constructed accordingly. The equations for aerodynamics considering static stability and control stability are shown in Equation 2.

$$\begin{cases} D = 0.5\rho V^2 S\,(C_D(\alpha) + C_D(\alpha,\delta_v)) \\ L = 0.5\rho V^2 S\,(C_L(\alpha) + C_L(\alpha,\delta_v)) \\ M = 0.5\rho V^2 S\,\bar{c}(C_m(\alpha) + C_m(\alpha,\delta_v)) \end{cases} \tag{2}$$

Vehicle Modeling: Through the above process, the entire mathematical modeling constructed is organized in the Earth Inertia Frame. Except for gravity acting on the same coordinate system, the thrust generated by the propeller and the aerodynamic forces generated by the wings were transformed in the body frame and wind frame, respectively, via the axis transformation matrix. The propeller thrust is expressed in the nose direction relative to the center of gravity of the aircraft, and the thrust of the front and rear propellers is (T_f) and (T_r) as the sum of the left and right thrusts. In addition, to consider the moment caused by thrust, the x-axis distance from the center of gravity to the front motor is expressed as (l_{x_f}), the z-axis distance is expressed as (l_{z_f}). In the case of the rear motor, it is expressed as (l_{x_r}) considering only the x-axis distance under the influence of the x-axis distance. The front propeller tilt angle is expressed as (δ_t) positively at $0deg$ in the vertical direction at $90deg$. Therefore, the longitudinal forces and moments acting on the aircraft by the propulsion system. The overall longitudinal forces and moments acting on the aircraft are organized in the Earth Inertia Frame and shown in equation 3.

$$\begin{cases} F_{X_E} = -D\cos(\theta-\alpha) - L\sin(\theta-\alpha) + T_f\cos(\theta+\delta_t) - T_r\sin\theta \\ F_{Z_E} = mg + D\sin(\theta-\alpha) - L\cos(\theta-\alpha) - T_f\sin(\theta+\delta_t) - T_r\cos\theta \\ M_{Y_E} = M + T_f(l_{X_f}\sin\delta_t - l_{Z_f}\cos\delta_t) - T_r l_{X_r} \end{cases} \tag{3}$$

3.2 Trim Analysis

Proposed Approach: The longitudinal trim analysis was performed to satisfy the steady-level flight. steady-level flight means maintaining altitude, attitude, and flight speed. Therefore, the force and moment in the longitudinal direction were made to satisfy that they are all zero, and the angle of attack and attitude angle can be assumed to be the same since it maintains altitude and attitude. As a result, the wind coordinate system and the Earth coordinate system are the same through the above assumption. Therefore, the trim analysis conditions and assumptions can be summarized as Equation 4, and the longitudinal model can be derived as Equation 5.

$$\begin{cases} \alpha = \theta \\ F_{X_E} = 0 \\ F_{Z_E} = 0 \\ M_{Y_E} = 0 \end{cases} \tag{4}$$

$$\begin{cases} q = 0.5\rho V^2 \\ F_{X_E} = -qS\,(C_D(\alpha) + C_D(\alpha,\delta_v)) + T_f\cos(\theta+\delta_t) - T_r\sin\theta \\ F_{Z_E} = mg - qS\,(C_L(\alpha) + C_L(\alpha,\delta_v)) - T_f\sin(\theta+\delta_t) - T_r\cos\theta \\ M_{Y_E} = qS\,\bar{c}(C_m(\alpha) + C_m(\alpha,\delta_v)) + T_f(l_{X_f}\sin\delta_t - l_{Z_f}\cos\delta_t) - T_r l_{X_r} \end{cases} \tag{5}$$

The eVTOL tiltrotor vehicle can control the flight status by the angle of attack, control surface, tilt angle, front motor thrust, and rear motor thrust. As a result, the aircraft can satisfy the trim conditions by controlling at different pitch angles at the trim analysis's flight speed. For this reason, it was analyzed as a way to provide tilt angle, flight speed, and angle of attack to derive controls that satisfy trim conditions. For trim analysis, Equation 6 and Equation 7

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derive the thrust required to maintain attitude and altitude depending on the control surface deflection angle and use the resulting data to derive the control values for flight speed maintenance using the bisection method. The trim analysis algorithm is shown in Algorithm 1.

$$\begin{cases} A_{11} = -\dfrac{\sin(\alpha+\delta_t)}{qS} \\ A_{12} = -\dfrac{\cos\alpha}{qS} \\ A_{21} = \dfrac{l_z\cos\delta_t - l_x\sin\delta_t}{qS\bar{c}} \\ A_{22} = \dfrac{l_x}{qS\bar{c}} \\ B_{11} = C_L(\alpha) + C_L(\alpha,\delta_v) - \dfrac{mg}{qS} \\ B_{21} = C_m(\alpha) + C_m(\alpha,\delta_v) \end{cases} \tag{6}$$

$$\begin{bmatrix} T_f \\ T_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}^{-1} \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix} \tag{7}$$

Algorithm 1 Trim Analysis Algorithm

Import the analysis point about the flight speed(V), angle of attack(α) and tilt angle(δ_t)

$q = 0.5\rho V^2$

for ($\delta_{v_{min}} \le \delta_v \le \delta_{v_{max}}$) **do**
  Find the appropriate curve (δ_v, ΣF_{X_E})
  Estimate the thrust required for maintenance of altitude and attitude
  Calculate the ΣF_{X_E} and store the data
  Make a Cubic spline which fit to ΣF_{X_E}
  Check the min, max in ΣF_{X_E}
  if ($\Sigma F_{X_{E\,min}} < 0$ & $\Sigma F_{X_{E\,max}} > 0$) **then**
    Find ΣF_{X_E} when it became 0 using bisection method
    $\delta_{v_{trim}} = bisection(Cubicspline, Sol_{min}, Sol_{max})$
    Calculate the actual thrust which satisfies the steady-level flight
    Calculate the effect on propeller inflow speed
    if ($0 \le T_{front} \le T_{max_{V_{front_{inflow}}}}$ & $0 \le T_{rear} \le T_{max_{V_{rear_{inflow}}}}$ & $\delta_{v_{min}} \le \delta_{v_{trim}} \le \delta_{v_{max}}$) **then**
      Calculate the objective function and save the trim results
    end if
  end if
end for

Tilt Corridor: This section outlines the process for deriving the tilt corridor through trim analysis. The tilt corridor is determined by specifying the operating range for flight speed, angle of attack, and tilt angle. A trim analysis is conducted within the specified range of flight speed and angle of attack with the tilt angle fixed to find the control surface deflection angle and thrust that satisfies steady-state level flight. Using the data obtained from the trim analysis, the minimum and maximum flight speeds that meet the trim conditions at a given tilt angle can be determined. By repeating this process for all tilt angle ranges, the minimum and maximum flight speeds across the entire operating range of tilt angles can be established. This allows for the determination of the minimum and maximum flight speed boundaries, which enables the derivation of the tilt corridor. Figure 3 illustrates the process diagram to determine the tilt corridor.

Tilt Angle Control Planning: In this section, we outline the procedure for deriving the tilt angle control plan through a trim analysis. The controls are determined based on the flight speed, tilt angle, and angle of attack. Therefore, the analysis can be performed based on the flight speed, tilt angle, and angle of attack. In this study, considering the operation of the aircraft, the angle of attack was determined according to the flight speed using the

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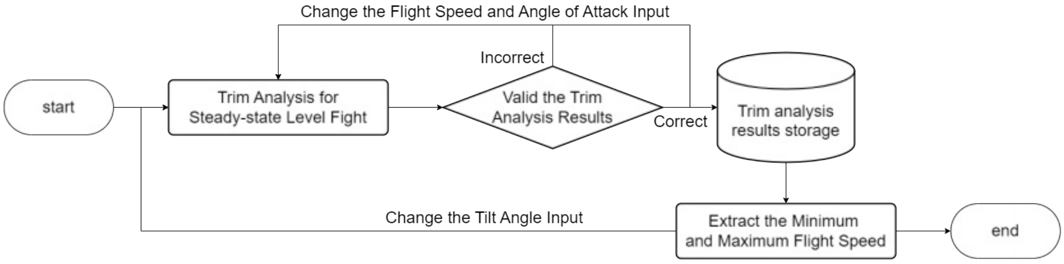

Figure 3: Tilt Corridor Process Diagram

predefined angle of attack schedule according to the passenger's comfortable with boarding or other purposes during the transition flight. The tilt angle control planning process is shown in Figure 4.

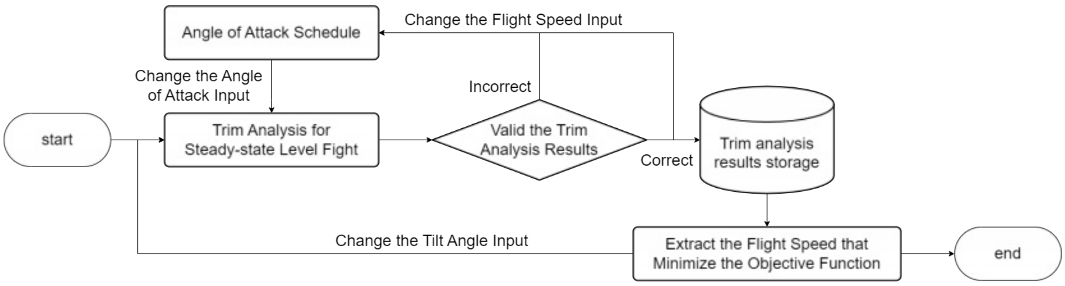

Figure 4: Tilt Angle Control Planning Process Diagram

4. Results and Analysis

4.1 Tilt Corridor

Trim analysis was performed within the operating range of the aircraft through the tilt corridor derivation process above. Depending on the operating range, the flight speed was analyzed from $0m/s$ to $40m/s$, angle of attack from $-10deg$ to $10deg$, tilt angle from $0deg$ to $90deg$. The analysis conditions are shown in Table 2, and the analysis results showing the data at 10 degrees intervals are shown in Table 3. The analysis determines the minimum and maximum flight speeds according to the tilt angles within the operating range and produces the tilt corridor of the gray area in Figure 5. According to the tilt corridor, the maximum speed increases from vertical to $70deg$ horizontally, the maximum speed from $70deg$ to horizontal is constant and then decreases slightly, and the minimum speed increases. This shows that the tilt angle is more advantageous for low-speed flight when facing vertically, and for high-speed flight when facing horizontally.

Table 2: Trim Analysis Condition

Parameter	Minimum Value	Maximum Value	Interval Value	Unit
Tilt Angle	0	90	1	deg
Flight Speed	0	40	0.1	m/s
Angle of Attack	-10	10	0.1	deg

4.2 Tilt Angle Control Plan

Following the tilt angle control planning process above, it is possible to derive tilt angle control plan that satisfies the objective function. In this paper, we used the minimum total thrust as the objective function as Equation 8. The reason for using the minimum total thrust as a function of purpose is that the propulsion system of the tiltrotor vehicle uses an electric propulsion system, and in general, the required power of the electric propulsion system is proportional to the thrust, so using less thrust uses less energy. The tilt angle control plan consists of two types: one derived using a predefined angle of attack schedule and the other derived without the angle of attack schedule. The derived tilt angle

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Table 3: Tilt Corridor Data

Tilt Angle (deg)	Minimum Flight Speed (m/s)	Maximum Flight Speed (m/s)
0	14.8	32.6
10	14.3	33.0
20	13.6	34.1
30	12.9	35.9
40	11.9	36.9
50	10.5	37.7
60	8.0	37.0
70	0.0	37.6
80	0.0	34.7
90	0.0	25.5

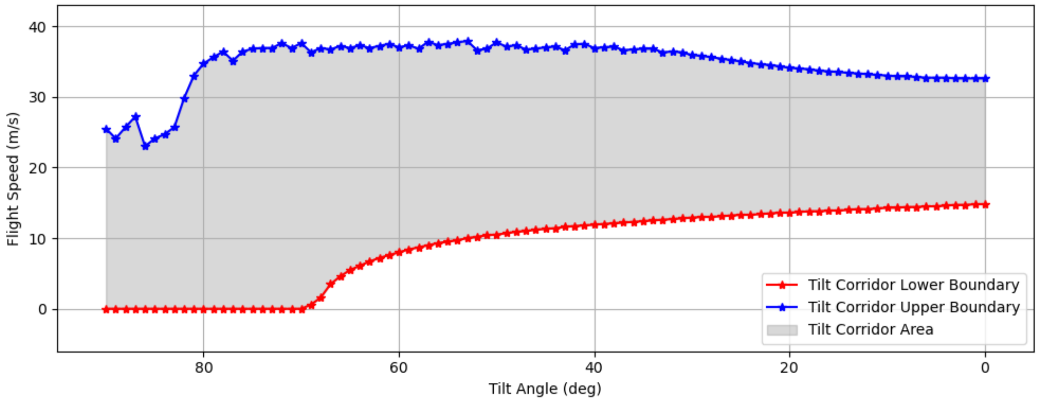

Figure 5: Tilt Corridor

control plan is shown in Figure 7. The predefined angle of attack was set to vary with flight speed in the form of a sine wave, as shown in Figure 6, from hovering to cruising. The hovering state is a flight speed of $0m/s$ and an angle of attack of $0deg$, while the cruising state is a flight speed of $24m/s$ and an angle of attack of $4.1deg$. As a result, the aircraft's attitude changes smoothly according to the angle of attack schedule, preventing flight instability due to rapid attitude changes during the transition flight. According to the results, when considering the angle of attack schedule from $90deg$ to $80deg$ of tilt angle, the tilt angle gradually changes, and the flight speed increases. However, in the case where the angle of attack schedule is not used, the aircraft lowers its nose at a tilt angle of $90deg$ to increase the flight speed, and when reaching a sufficient speed, it gradually changes the tilt angle. Both types of aircraft then gradually increase the flight speed while the tilt angle changes from $80deg$ to $0deg$.

$$f_{object} = T_f + T_r \tag{8}$$

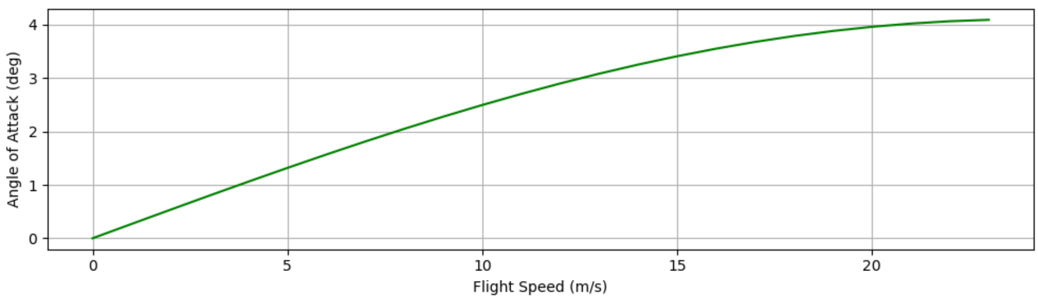

Figure 6: Angle of Attack Schedule

The difference in control results between the two types is mainly observed between tilt angles of $90deg$ and $80deg$. In this range, when not considering the angle of attack schedule, the forward thrust is maintained significantly

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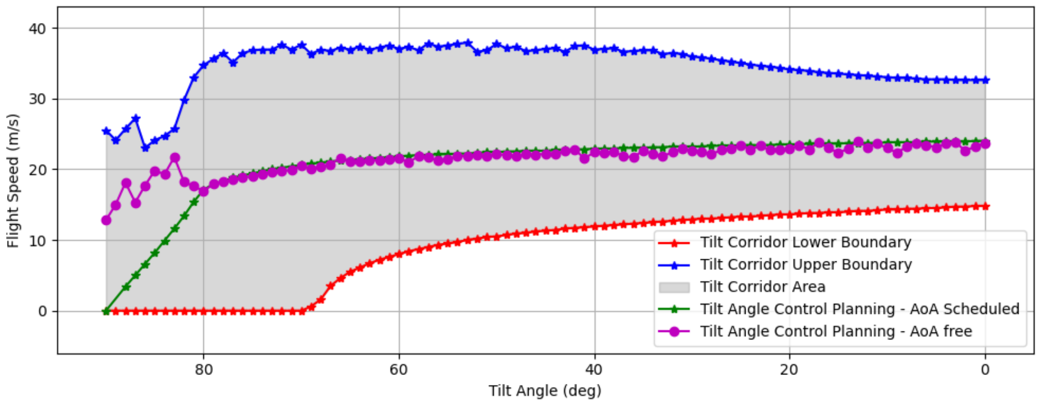

Figure 7: Tilt Angle Control Plan

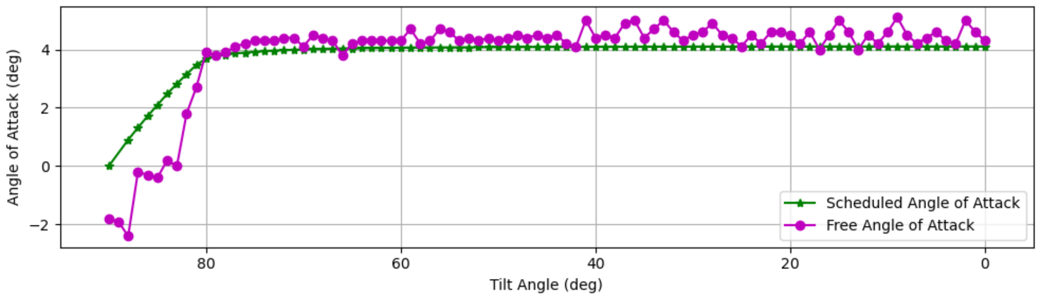

Figure 8: Angle of Attack Comparison

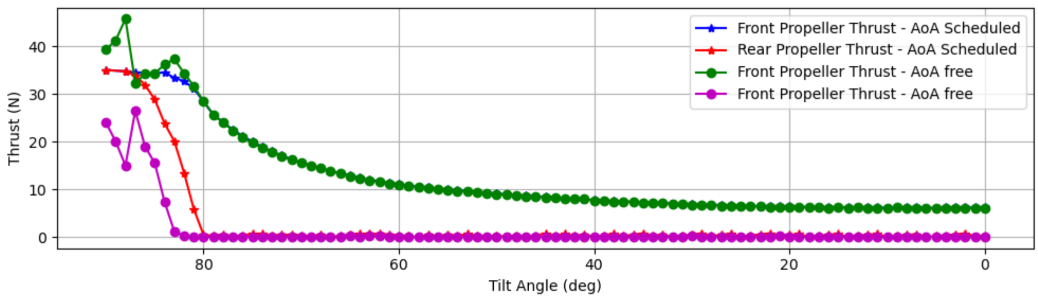

Figure 9: Thrust Comparison

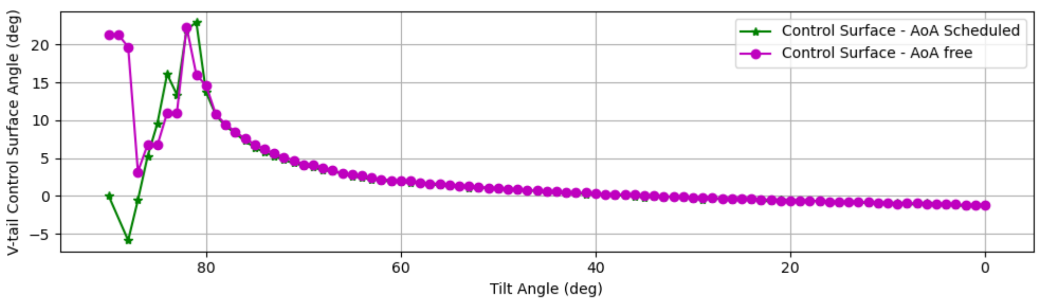

Figure 10: Control Surface Comparison

higher than the rear thrust to lower the angle of attack and increase the flight speed. Additionally, negative moments are generated through control surfaces to counteract the positive moments caused by thrust. On the other hand, when

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considering the angle of attack schedule, the pitch gradually changes to a trim angle for cruising, resulting in a smooth change in thrust control and control surface deflection. Through these results, it is confirmed that considering the angle of attack schedule minimizes the aircraft's attitude changes during the transition flight and provides smoother control variations. The comparison of the angle of attack control changes can be seen in Figure 8, the comparison of thrust control changes in Figure 9, and the comparison of control surface deflection changes in Figure 10.

5. Conclusion

The development of UAM vehicle control and operations for passenger comfortability and safety is significantly advanced by this work, which proposes a tilt angle control planning methodology for eVTOL aircraft during the transition phase, strictly considering the requirements of UAM flight operations. Unlike previous studies that often treat pitching behaviors as typical for unmanned aerial vehicles (UAVs) and disregard human-oriented comfortability in transition, our approach takes into account human comfort and adopts trim analysis to generate a comprehensive tilt angle control plan. This plan incorporates the angle of attack schedule based on flight speed, allowing for precise control of tilt angle, angle of attack control, thrust, and control surfaces. Overall, this research contributes to enhancing UAM vehicle control and operations, ensuring passenger comfort and safety.

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