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SOFTWARE SIMULATION OPTIONS FOR EVTOL TILTWING CONFIGURATIONS

Kukla O.[1]

Abstract: *Tilt-wing electric vertical takeoff and landing (eVTOL) aircraft exhibit strongly nonlinear and configuration-dependent dynamics, with the transition between hover and forward flight representing the most challenging regime to model. While rigid-body dynamics follow conventional aircraft formulations, continuously varying aerodynamic and propulsive characteristics associated with wing tilt significantly increase modeling complexity.*

This paper discusses software-based simulation approaches for tilt-wing eVTOL aircraft with a focus on continuous transition modeling. The wing tilt angle is treated as a continuous state, and aerodynamic and propulsive forces are parameterized as functions of airspeed, angle of attack, and wing tilt. Special attention is given to propulsion–airframe interaction effects and to the representation of path-dependent (hysteresis) behavior through propulsion-dependent aerodynamic parameterization. The proposed approach enables continuous simulation of transition dynamics without introducing discrete mode switching.

Keywords: eVTOL, Tiltwing Aircraft, Flight Dynamics Simulation, Project MiYa

1. Introduction

Tilt-wing electric vertical takeoff and landing (eVTOL) aircraft operate across three distinct flight regimes. In forward flight, the wing is aligned with the freestream and the vehicle behaves similarly to a conventional fixed-wing aircraft. In hover, the wing is rotated to a near-vertical orientation and lift is generated primarily by the propulsive system, resulting in helicopter- or multicopter-like behavior. The transition regime spans the continuous range of intermediate wing tilt angles and occurs during both acceleration from hover to forward flight and deceleration during approach and landing.

The transition phase represents the most challenging regime from a modeling and simulation perspective. Strongly nonlinear aerodynamics, rapidly changing propulsion effects, and pronounced coupling between wing orientation, vehicle attitude, and control effectiveness limit the applicability of classical steady-flight assumptions. Accurate representation of this regime is therefore essential for simulation-based analysis, control design, and evaluation of abnormal or degraded flight conditions.

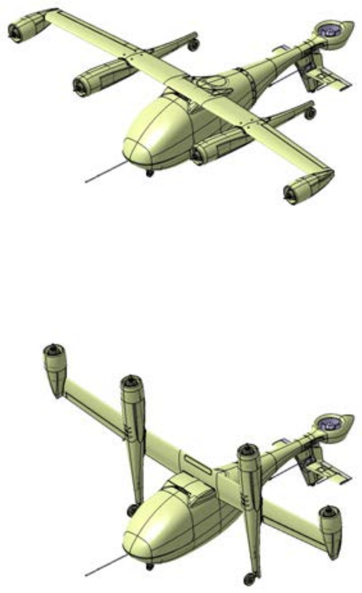

Fig. 1–2: MiYa eVTOL configuration.

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[1] Bc. Ondrej Kukla: Czech Aerospace Research Centre (VZLU Aerospace), Beranových 130; 199 00, Prague; CZ, kukla@vzlu.cz

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This paper focuses on software-based simulation modeling of tilt-wing eVTOL aircraft, with emphasis on continuous representations of transition dynamics. The wing tilt angle is introduced as an explicit state variable, and aerodynamic and propulsive effects are parameterized as functions of flight condition and propulsion state. Particular attention is given to propulsion–airframe interaction and to the representation of path-dependent behavior through continuous, propulsion-dependent aerodynamic modeling. The approach is demonstrated on a tilt-wing configuration developed within the MiYa project (VZLU Aerospace, 2025).

2. Continuous Tilt-Wing Transition Modeling

Unlike steady forward or hover flight, the transition regime exhibits strongly nonlinear and configuration-dependent dynamics. Experimental and numerical studies show that aerodynamic forces and moments during transition are not solely functions of the instantaneous configuration. In particular, unsteady simulations indicate that the aerodynamic response differs depending on whether the wing is tilting toward forward flight or toward hover, revealing direction- and path-dependent behavior in the transition dynamics (Huang, 2024).

To capture this behavior within a continuous framework, the wing tilt angle must be treated as an explicit modeling variable rather than a discrete mode identifier. Aerodynamic and propulsive forces are parameterized as functions of airspeed, angle of attack, and wing tilt angle based on wind-tunnel measurements or CFD data, enabling smooth variation of forces and moments while preserving the strong coupling between vehicle attitude, wing orientation, and propulsion.

The hysteresis effect between hover and forward flight does not originate in the static aerodynamic characteristics. Instead, the aerodynamic coefficients are additionally parameterized by the thrust coefficient T_{Cs}, which depends on the propulsion system state. As the wing is influenced by both the freestream and the propeller slipstream, an effective dynamic pressure q_s is introduced as

$$q_s = q + \frac{\overline{T}}{A_p}, \tag{1}$$

from which the thrust coefficient is defined as

$$T_{Cs} = \frac{\overline{T}}{q_s A_p}. \tag{2}$$

In both expressions, the total thrust $\overline{T}$ and propeller area A_p play a central role. The hysteresis arises from differences in propeller operating conditions during acceleration and deceleration. During transition from hover to forward flight, higher RPM (and thus thrust) is required to accelerate the aircraft, whereas during deceleration lower thrust is sufficient to maintain trimmed flight. This asymmetry directly affects the thrust coefficient T_{Cs} and introduces path-dependent aerodynamic behavior.

To illustrate this effect, three wing transition trajectories with constant translational accelerations were defined, bringing the aircraft from hover (horizontal speed 0.1 m/s) to forward flight (wing tilt 30° and speed 25.5 m/s), and back.

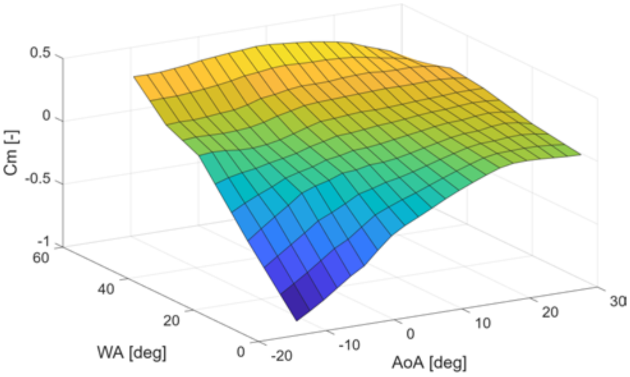

Fig. 3: Static pitch moment coefficient of the MiYa tilt-wing eVTOL aircraft obtained from wind tunnel measurements, shown for zero sideslip and a thrust coefficient of $T_{Cs} = 0.25$.

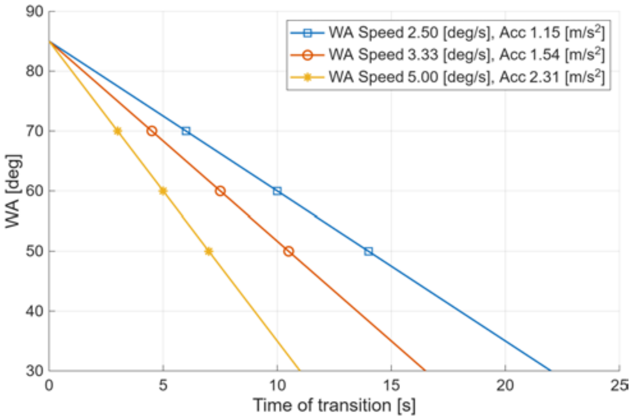

Fig. 4: Wing tilt transition trajectories for the three acceleration profiles considered.

Trimmed states of the aircraft were computed at the initial and final conditions (zero acceleration), as well as at wing tilt angles of 70°, 60°, and 50° for each acceleration level. The resulting differences in required propeller RPM between acceleration and deceleration are shown in Fig. 5. This demonstrates that hysteresis can be represented within a continuous model through propulsion-dependent aerodynamic parameterization, without introducing discrete mode switching.

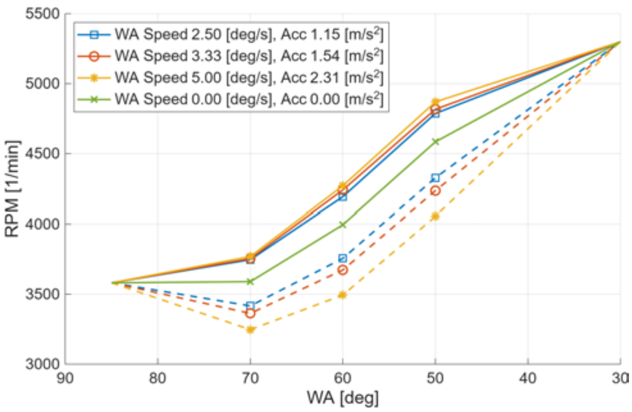

Fig. 5: Propeller RPM during acceleration (solid line) and deceleration (dashed line), illustrating hysteresis. The steady-flight (trimmed, no transition) RPM values are shown in green for comparison.

2.1. Propeller Force and Moment Contributions

The force and moment contributions of wing-mounted propellers must be carefully considered within the overall aircraft dynamics, particularly when differential thrust is included for control design or failure-case and degraded flight condition simulations. The total moment acting on the aircraft in the body coordinate system can be expressed as

$$[m]^B = [m_a]^B + [S_{CLB}]^B[F_a]^B + [m_{prop}]^B + [m_{ctrl}]^B, \tag{3}$$

where $[m_a]^B$ and $[F_a]^B$ denote aerodynamic moments and forces, $[S_{CLB}]^B$ represents the skew-matrix form of the moment arm from the center of lift to the center of gravity, $[m_{prop}]^B$ captures propulsion-induced moments, and $[m_{ctrl}]^B$ accounts for control effects from the aircraft's stabilizer and tail mounted ventilator.

During transition flight, the propulsion term becomes particularly significant. At higher levels of deployment, wing-mounted propellers contribute significantly to the pitching moment, first through their direct thrust force and second through their normal thrust component, which becomes non-zero at higher incidence angles. The propeller force coefficients c_T, c_N, and c_P are modeled as functions of the effective incidence angle,

$$AOI = AoA + WA + \delta Na. \tag{4}$$

The effective propeller incidence angle captures the combined influence of vehicle angle of attack, wing tilt, and nacelle orientation with respect to the wing on propeller force generation.

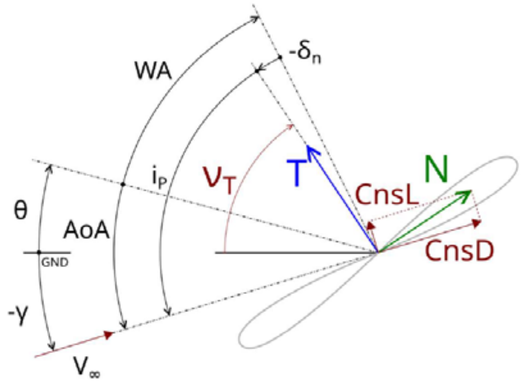

Fig. 6: Direct and Normal thrust components generated by the propeller under incidence angle.

The resulting propulsion forces $[F_T]^{Na}$ and $[F_N]^{Na}$ representing the direct and normal thrust components are transformed into the body coordinate system and contribute to both translational forces and rotational moments acting on the aircraft.

$$\begin{aligned} [m_{T_i}]^B &= [S_{Na_iB}]^B[T]^{BNa}[F_{T_i}] \\ [m_{N_i}]^B &= [S_{Na_iB}]^B[T]^{BNa}[F_{N_i}] \end{aligned} \tag{5}$$

where the matrices $[S_{Na_iB}]^B$ are the skew-matrix form of displacement vectors $[s_{Na_iB}]^B$ pointing from aircraft's center of gravity to the tip of the i-th nacelle (root of the propeller). The transformation matrix

$[T]^{BNa}$ is itself a function of the wing tilt angle WA modified for the nacelle orientation angle δNa. The displacement vector is constructed with the knowledge of the position of the wing tilt joint with respect to center of gravity and position of the i-th nacelle in respect to the joint as:

$$[s_{Na_iB}]^B = [T]^{BNa} \begin{bmatrix} r_i \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ l_i \\ 0 \end{bmatrix} \tag{6}$$

where r_i is the distance of the point Na_i from point J along the $[x]^{Na}$ axis and l_i is the distance of the same point with respect to J along the $[y]^{Na}$ axis. The nacelle coordinate system $]^{Na}$ is in unity with the aircraft's body system $]^{B}$ for $WA + \delta Na = 0$. (Zipfel, 2014).

2.2. Propeller-Induced Flow Effects on Control Surfaces

Another significant effect of propeller–wing coupling is the change in aileron functionality across flight regimes. In forward flight, the ailerons are influenced by both the freestream and the propeller slipstream, and therefore behave similarly to those of a conventional fixed-wing aircraft, producing roll about the $[x]^B$ axis. However, their effectiveness is modified by the increased local flow velocity and disturbances induced by the propellers.

In hover, where the freestream velocity is negligible, the airflow over the ailerons is dominated by the propeller slipstream. Due to the near-vertical orientation of the wing, the control action no longer produces a conventional rolling moment, but instead induces rotation primarily about the $[z]^B$ axis.

These propeller-induced flow effects introduce strong state- and configuration-dependent variations in control effectiveness. In particular, the aerodynamic response of the control surfaces becomes a function of wing tilt angle, propulsion state, and local flow conditions. Within a continuous modeling framework, this behavior can be represented by parameterizing control surface effectiveness with respect to these variables, allowing smooth variation of control authority across the transition regime.

3. Conclusions

This paper has presented a continuous modeling approach for tilt-wing eVTOL flight dynamics, emphasizing wing tilt as an explicit state variable and the role of propulsion–airframe coupling. A key result is that path-dependent (hysteresis) behavior can be represented without introducing discrete mode switching or jump functions. Instead, hysteresis emerges naturally through propulsion-dependent aerodynamic parameterization, where thrust level and effective dynamic pressure govern the aerodynamic coefficients. This enables continuous representation of transition dynamics across both acceleration and deceleration phases within a unified formulation. The presented framework provides a consistent basis for simulation of tilt-wing eVTOL aircraft across the entire transition envelope.

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