Wind Tunnel Investigation of Stationary Straight-Lined Flight of Tiltwings Considering Vertical Airspeeds

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Abstract

Tiltwings are aircraft with a wing that can be rotated around the lateral axis of the aircraft. Inside the flight envelope of tiltwing aircraft, significant changes in aerodynamics and flight mechanical behavior occur. This paper proposes a way of gathering required data to design a controller for straight-lined flight in wind tunnel investigation. Special attentions is given to vertical airspeeds. Furthermore a method to simulate flight states of climbs and descents in wind tunnels is described. Wind tunnel investigations were carried out for a small demonstrator aircraft and results are discussed with focus on characteristic aerodynamic properties of tiltwings.

Nomenclature

α_F	Fuselage Angle of Attack
γ	Flight Path Angle
σ	Tilt Angle
θ_F	Fuselage Pitch Angle
G	Weight
u	Horizontal Airspeed
V_a	Total Airspeed
w	Vertical Airspeed
X^f	Horizontal Force (body fixed)
Z^f	Vertical Force (body fixed)

1 Introduction

Tiltwing aircraft combine VTOL capabilities with high cruise speeds and endurance. This combination of features is due to the ability to vary the angle of the wing and attached main engines from a conventional, fixed wing aircraft like position (wing-borne flight) to an upward orientation (thrust-borne flight). These changes in relative orientation of wing and fuselage result in significant variations of aerodynamic and flight mechanical properties of a tiltwing aircraft and therefore require special consideration in flight controller design.

These changes in flight mechanical properties can be considered in complex mathematical models (for example in [2], [10]). Typically not all aerodynamic effects are considered in mathematical models, as shown in comparison to wind tunnel experiments [4]. A combined approach utilizing both mathematical simulation of the aerodynamic properties and data acquired in wind tunnel investigations is proposed in [7]. This data is used to design controllers accounting for the special and complex requirements resulting from the changes in flight mechanical properties [8].

[3] as well as [9] propose a controller that allows stationary operation of a tiltwing at any desired forward airspeed in a range from zero to the maximum allowable operation speed of the particular aircraft. The proposed controller is based on superposition of control surface deflections (including thrust and tilt angle) needed for a stationary flight in the commanded flight state (trim deflections) and deflections necessary for attitude control. This controller does not consider vertical airspeeds or fuselage pitch angles other than zero and it was assumed that a flight state is described precisely enough by the forward airspeed. As a result flight tests indicated shortcomings in flight states with considerable vertical airspeed or fuselage pitch angle. A change of flight state is achieved by a slow change of the commanded flight state and with it the commanded trim deflections.

An improved controller has since been developed to address these issues and to allow a deliberate and rapid change of flight state. Trim deflections, control surface deflections for attitude control and those necessary for accelerations to change the flight state are computed utilizing characteristic maps, which are dependent on the flight state. The flight state is described by the combination of horizontal and vertical airspeed in the new controller. A value of the fuselage pitch angle, which is appropriate for practical tiltwing operations is mapped to these airspeeds. The required data to generate these characteristic maps has been acquired in wind tunnel investigations.

This paper describes necessary considerations to simulate flight states of straight-lined flight, including climbs and descents in a wind tunnel and the acquisition of the necessary data to generate the characteristic maps. Furthermore the gathered data is discussed and results are presented.

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2 Tiltwing Flight Mechanics

In this chapter special aspects of tiltwing flight mechanics in comparison to fixed-wing aircraft flight mechanics are examined. The tiltwing aircraft's wing can be deliberately rotated 90° around the lateral axis of the fuselage. This rotation is described in terms of the tilt angle σ. Engines are mounted to the wing; thus, rotation of the wing comes along with thrust vector rotation. This property constitutes VTOL capabilities of tiltwing aircraft. Compared to fixed-wing aircraft, tiltwing aircraft feature additional control surfaces. Most notably, the tilt angle makes an additional control surface. The tiltwing's engine configuration (at least two main engines mounted to the wing) adds the ability to control moments by asymmetric throttle setting. The corresponding *control surface* is called differential thrust. To maintain controllability of pitching moment in flight states of negligible incident flow (hovering for example) the elevator has to be complemented by an additional control surface. A tail rotor is one feasible choice here. Unlike the elevator, aileron effectiveness is maintained in all flight states by the propeller's slipstream. In the following text, elevator and the complementing control surface, as well as differential thrust and rudder (which may be omitted, see Sec. 3.2) are respectively treated as one combined control surface. Thus, this paper considers tiltwing aircraft to feature one additional control surface compared to fixed-wing aircraft. At the same time the relative motion between wing and fuselage adds an additional degree of freedom to the tiltwing's motion.

For fixed wing aircraft, a trim state of stationary straight-lined flight can be described by the three state variables horizontal airspeed u, vertical airspeed w, and fuselage pitch angle θ. For conventional fixed-wing aircraft (without flaps) only two of these states can be set independently. If airspeeds are given, pitch angle θ depends on the required angle of attack to maintain adequate lift. The situation is different for tiltwing aircraft: Making use of the additional dimension of freedom and additional control surface, all three state variables can be set individually as the wing's angle of attack is independent of the fuselage pitch angle.

The newly proposed flight-controller is based upon trimmed stationary straight-lined flight states. Trim control surface deflections are maintained by a dedicated, map-based feedforward controller. As the aircraft configuration (in particular tilt angle) changes with different trim states, the effectiveness of control surfaces changes as well. To enable the flight control system to perform well within the entire flight envelope, these changes should be known to the controller. Therefore the effectiveness of each control surface as well as trim control surface deflections are available as functions of the trim state in form of various characteristic maps. These maps are object of investigation in this paper. To reduce the dimension of domain of all characteristic maps, a particular value for the fuselage pitch angle is determined during wind tunnel measurements dependent on horizontal and vertical airspeeds. The pitch angle is chosen in a feasible way for practical tiltwing applications. For low horizontal airspeeds (typical during vertical takeoff and landing) the pitch angle is fixed to zero; for high horizontal airspeeds fuselage pitch angle is chosen analogous to fixed-wing configurations. The fuselage pitch angle is discussed in more detail in Sec. 4.1.

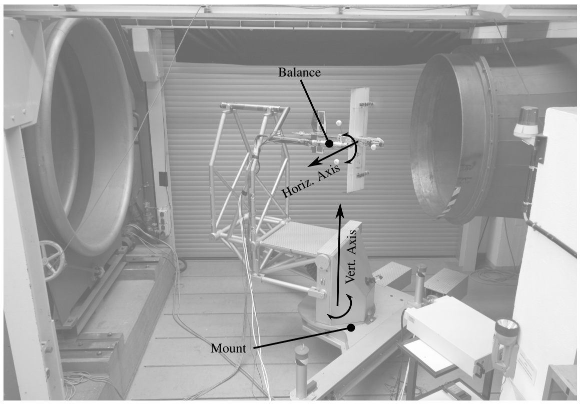


Figure 1: Aircraft Positioned in the Wind Tunnel

3 Wind Tunnel Investigation

The characteristic maps of control surface trim deflections and effectiveness are generated by interpolation of data measured in wind tunnel investigations at discrete points distributed across the domain of the characteristic maps. This domain is the flight envelope regarding horizontal and vertical airspeeds. At each of these points a stationary flight state is trimmed (trim state). The corresponding control surface deflections are the corresponding trim deflections of this flight state. Additionally the deflection of each control surface is sequentially changed, in order to determine the effect on external forces and moments. These changes in forces and moments can be normalized to a full deflection of the considered control surface and yield an effectiveness matrix in each trim state. The inversion of this effectiveness matrix is used by the controller to calculate the necessary control surface deflections for attitude control and a change of flight state.

The measurements are conducted in a return-flow wind tunnel with an open measurement section that is big enough to accommodate the investigated aircraft in full scale and flight-ready condition. The aircraft is attached to a two axis mount with a six-component strain gauge balance measuring forces and moments (see Fig. 1).

3.1 Demonstrator Aircraft

The investigated aircraft MAVERIX has an overall takeoff mass of 1,7 kg and a wingspan of 0,96 m. It is powered by two electric main engines driving fixed pitch propellers. Control surfaces include an elevator, ailerons, thrust, differential thrust, and tilt angle. The elevator is supported by a fixed speed, variable pitch tail rotor. A rudder surface is not included. Control surface deflections are measured in a normalized manner; thrust ranges from zero to one, all others from minus to plus one. The tilt angle is an exception and is measured in radians ranging from 0 (wing-borne flight) to $\frac{\pi}{2}$ (thrust-borne flight).

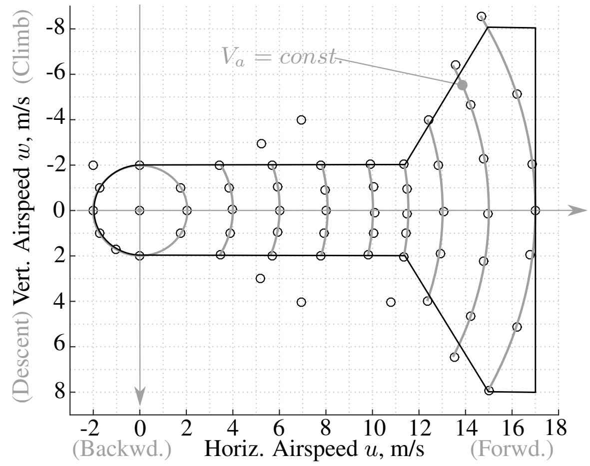


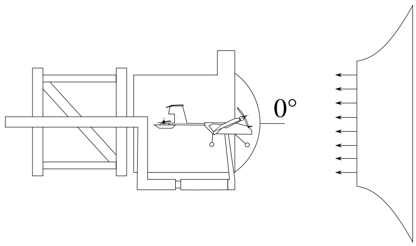
Figure 2: Flight Envelope and Measured Trim States

3.2 Trim States

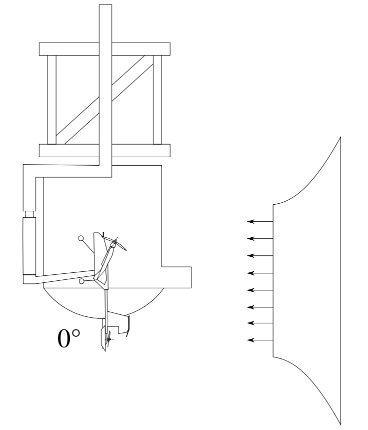
The flight envelope has been defined based on flight tests conducted with the help of the former controller design (see Fig. 2). In thrust-borne flight the maximum vertical airspeed that can be flown without limitations in controllability (especially in pitch control) is approximately 2 m/s. The aircraft demonstrated significant higher climb and descent performance in wing-borne flight than in thrust-borne flight, which results in higher allowable vertical airspeeds in wing-borne flight compared to thrust-borne flight. The wind tunnel investigations were aimed at finding a safely flyable envelope. The flight envelope has been shaped symmetrical to the horizontal flight (no vertical airspeed) and rather conservatively with respect to maximum allowable airspeeds.

The flight mechanical properties inside the entire flight envelope have to be described sufficiently on the basis of the data acquired in wind tunnel investigations. As a result a set of trim states distributed across the flight envelope has been measured. Due to wind tunnel limitations the maximum total airspeed V_a that can be investigated is 17 m/s. In order to reduce workload, the measured trim states are selected in a way, that the operational airspeed of the wind tunnel has to be changed as rarely as possible. This results in a distribution of the measured trim states in polar coordinates of constant total airspeed V_a. Aerodynamic loads change in particular during wing-borne flight (13 m/s to 17 m/s) with the dynamic pressure and thus quadratic with total airspeed V_a. This dependency results in the need for at least three trim states measured in the direction of increasing total airspeed in wing-borne flight. With changing tilt angle the aircraft configuration changes significantly and dependencies of external forces and moments are subject to investigation. The 2 m/s grid spacing in total airspeed V_a between measured trim states used in wing-borne flight has been applied at lower airspeeds as well. Functional dependencies on vertical airspeeds are unknown, since the configuration of the aircraft changes at a change of vertical airspeed w and aerodynamic effects like buffeting are to be expected [6]. In order to measure effects of vertical airspeeds, at least five trim states are chosen at a constant total airspeed V_a in the direction of a variation in vertical airspeed w (or, respectively, in polar coordinates the flight path angle γ). Further trim states have been measured to verify performance limitations that have been found during the wind tunnel investigations (see Sec. 4.3).

The direction of incident flow relative to the fuselage varies from backward, top (steep climb at low horizontal airspeed), forward to bottom (steep descent at low horizontal airspeed). This range of the angle of attack of 360° requires various mounting positions of the aircraft in the wind tunnel. Fig. 3 shows exemplary the mounting positions for forward flight and shallow climbs and descents (Fig. 3a) and a backward climb (Fig. 3b). The aircraft is mounted at a roll angle of 90° in order to use the larger travel of approx. 90° of the mount around the vertical axis to adjust the angle of attack of the aircraft. In comparison the travel around the horizontal axis is just 28° (see Fig. 1).



(a) Forward Flight, Shallow Climb/Descent



(b) Backward Flight and Climb

Figure 3: Exemplary Mounting Positions (Top View)

3.3 Simulation of Trim State Conditions

A trim state in straight-lined flight is characterized by a stationary equilibrium of forces and moments. An equilibrium of moments in the longitudinal motion can be achieved with a deflection of the elevator or the pitch of the installed tail rotor. The equilibrium of forces is governed by thrust, the force of gravity relative to the aircraft and the incident flow (angle of attack α and total airspeed V_a). Thrust, lift and drag have to be adjusted accordingly. Since the orientation of gravity relative to the incident flow is constant in a wind tunnel, a trim state has to be simulated under disregard of the actual gravitational load. The resultant of all forces (lift, drag, thrust) has to equal a virtual weight $\vec{G}$ of the aircraft. The orientation of this resultant force determines the orientation of gravity in the simulated trim state and thus yields the fuselage pitch angle θ_F (see Fig. 4). In the wind tunnel, the resultant force and its orientation can be determined from the forces measured by the balance in x- and z-direction (X^f

and Z^f). These two forces are influenced by changes in control surface deflections (again including thrust) and the angle of attack α. The angle of attack α itself can be adjusted and measured by the mount. With a known fuselage pitch angle θ_F and angle of attack α the flight path angle γ is known as well. The flight path angle γ and the total airspeed V_a define the trim states as mentioned in Sec. 3.2 (see Fig. 4 as well). Since the total airspeed V_a is adjustable with the wind tunnel controls, all trim states can be simulated.

A trim state condition is achieved by iteratively adjusting the angle of attack, tilt angle of the wing and thrust to set the equilibrium of forces and adjusting the elevator and tail rotor pitch for an equilibrium of moments. The required control surface deflections for an equilibrium of forces and a simultaneous equilibrium of moments are called trim deflections and trim fuselage pitch angle θ_F, which is mapped to the the horizontal and vertical airspeed defining the trim state. Once the trim state condition is reached, the control surface deflections are varied sequentially to determine the corresponding effectiveness matrix. To check for linear behavior, control surfaces are deflected positively and negatively, with a big and a small amplitude, superpositioned to the trim deflection. The effectiveness of a control surface on a certain force or moment is determined by averaging over the change in force or moment divided by the corresponding amplitude in control surface deflection (mean of normalized effectiveness).

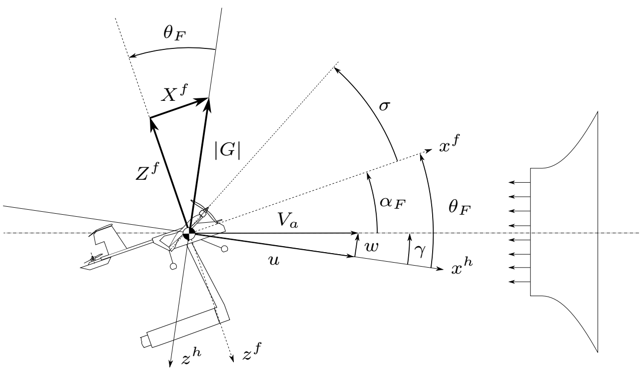


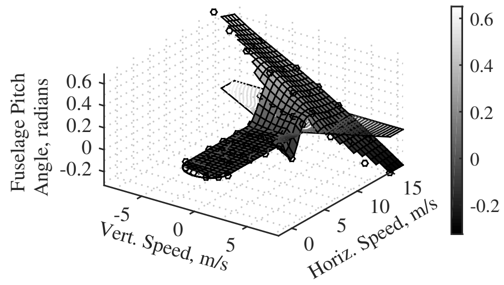
Figure 4: Simulated Trim State

4 Results

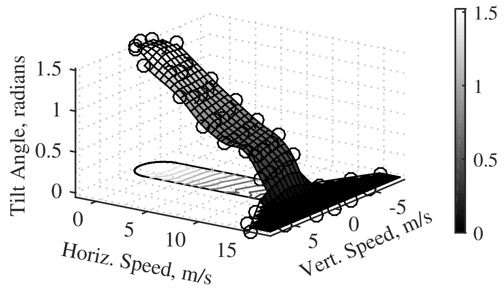
In the following section the results of the wind tunnel investigation are presented and discussed. Special attention is given to characteristic aspects of the tiltwing configuration. Note that the airspeeds used in the following plots are given in a horizontal body fix coordinate system.

4.1 Trim Deflections

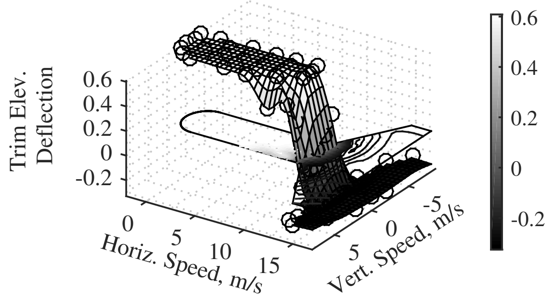
In thrust-borne flight (airspeeds up to 10 m/s) the equilibrium of forces is achieved by adjustment of tilt angle, amongst others. In wing-borne flight (airspeeds exceeding 13 m/s) the equilibrium is achieved by adjustment of the fuselage pitch angle. The tilt angle is zero in wing borne flight (configuration like a conventional fixed wing



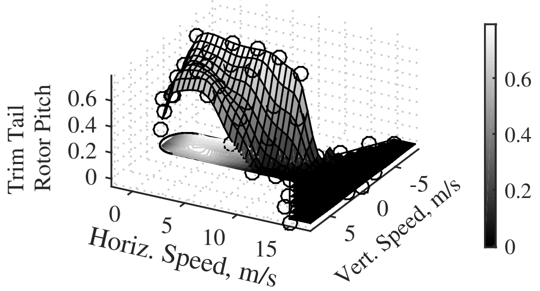
(a) Trim Fuselage Pitch Angle



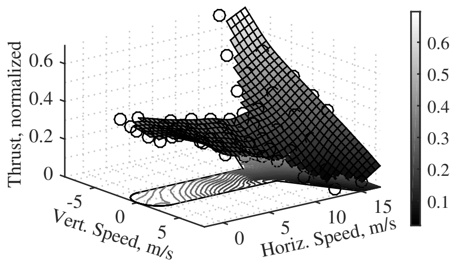
(b) Trim Tilt Angle



(c) Trim Elevator Deflection



(d) Trim Tail Rotor Pitch



(e) Trim Thrust Setting

Figure 5: Trim Deflections

aircraft, see Fig. 5b). In wing-borne flight, the pitch angle increases with decreasing vertical airspeed[1] (see Fig. 5a) and decreases with increasing total airspeed, since the angle of attack required to produce the necessary lift decreases with increasing dynamic pressure (see Fig. 4, [1]). In the proximity of the trim state at a horizontal airspeed of 10 m/s and a vertical airspeed of 2 m/s severe low-speed buffeting caused by the wake of stalled wing dictates a reduction of pitch angel. This allows the turbulent wake of the wing to flow underneath the horizontal tail plane as described in [6].

At low airspeeds the effectiveness of the elevator is insufficient to compensate the nose-down pitching moment caused by the relative position of the center of gravity and the line of action of the main engines' thrust (see Fig. 5c). At these trim states the elevator is deflected to its maximum allowable trim deflection that gives sufficient control reserve. The elevator is supplemented by the tail rotor (see Fig. 5d). The effect of vertical velocity can be seen clearly in the plot of the trim deflection of tail rotor pitch. In thrust-borne flight, a lower deflection is necessary in a descent than in a straight and level flight, since the nose-down pitching moment is reduced with increased upward incident flow. The opposite is true for a climb. The trim deflection of the tail rotor pitch is close to the maximum deflection in climbing thrust-borne flight states. This suggests proximity to a boundary in controllability due to limited pitch authority. In wing-borne flight the tail rotor pitch can be set to neutral since the elevator on its own is sufficient for pitch control which allows the tail rotor to be turned off. The nose-down pitching moment changes with increasing airspeed to a nose-up pitching moment, as it is typical for a longitudinally stable fixed wing configuration.

Starting at zero airspeed, trim thrust settings decrease initially with increasing airspeed since with increasing dynamic lift of the wings less thrust is required to compensate the weight of the aircraft (see Fig. 5e). Approaching wing-borne flight, aerodynamic drag exceeds the thrust required for weight support and trim thrust settings start to increase. Thrust required to climb is generally higher than in straight and level flight or in a descent at the same total airspeed. The steepest stationary descent is limited by the minimum thrust delivered with both engines idling. This boundary is found in wing borne flight at the highest measured descent rate. In these trim states aerodynamic drag is still sufficient to prevent an increase of airspeed due to gravitation.

Due to a symmetrical design of the aircraft relative to its vertical plane, aileron deflection and the differential thrust setting are zero in a trim state of straight-lined flight.

4.2 Control Surface Effectivness

Control surface effectiveness is a quantification of the extent, in which the equilibrium of forces or moments is disturbed by a full deflection of a control surface in a trim state. Four effectivenesses are discussed exemplarily in the following (see Fig. 6).

The main effect of an aileron deflection is a yawing moment in low speed flight. Effectiveness on rolling moment increases while effectiveness on yawing moment decreases as tilt angle is reduced with increasing airspeed (see Fig. 6a and Fig. 6b). The rolling moment caused by aileron deflection shows good compliance with theory, since it is approximately quadraticly dependent on total airspeed. The effectiveness of ailerons on yawing moment is significantly influenced by vertical airspeed in thrust-borne flight. The effectiveness is increased in climbs and decreased in descents relatively to straight and level flight since the additional incident flow adds to, or reduces the propeller slip stream flowing over the ailerons. In wing-borne flight the aircraft shows atypical fixed wing characteristics since there is negative adverse yaw, aileron deflection causes skidding rather than slipping in a turn. The ailerons are constructed in a way that increases drag on the upward deflected aileron more than the induced drag on the side of the downward deflected aileron increases.

An upward directed vertical force[2] is in thrust-borne flight primarily caused by an increase of thrust (see Fig. 6c). With a reduction of tilt angle at increasing airspeed the effectiveness of thrust on vertical force decreases. In wing-borne flight a vertical force is therefore produced by an increase of wing pitch angle either by an increase of fuselage pitch angle or tilt angle (see Fig. 6d).

4.3 Perfomance Limitations

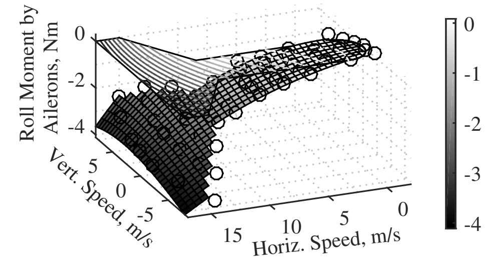
A summary of flight performance limiting aspects revealed by the wind tunnel investigations is shown in Fig. 7. Maximum climb rate is limited at low airspeeds by the maximum nose-down pitching moment that can be achieved with the tail rotor. At higher climb rates control authority in pitch movement is insufficient to guarantee safe operation. At flight states with a high angle of attack of the wing low speed buffeting was experienced. At the measured trim point of maximum descent at a total airspeed V_a of 10 m/s airframe vibrations caused by the turbulent wake were severe enough to require a change in pitch attitude to reduce vibrations. This low speed buffeting is a problem inherently caused by the tiltwing configuration and the all-moving wing. In wing-borne flight at airspeeds exceeding 13 m/s, the maximum rate of stationary descent is limited by the drag of the aircraft with both engines idling, a descent at a steeper angle with a given airspeed in this range would result in an accelerated flight state, since an equilibrium of forces cannot be achieved.

4.4 Relation Between Throttle Setting and Thrust

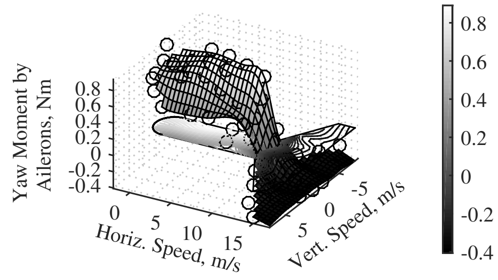
Thrust is controlled by the command variable throttle. The absolute thrust delivered by the engines depends on incident flow, battery voltage and throttle setting. A linear dependency between thrust and throttle setting can not be assumed generally, but is a requirement by the controller in order to be able to superposition control surface deflections correctly. The thrust at a set airspeed and throttle setting can be divided by the maximum available thrust (full throttle) at the same airspeed. Fig. 8 shows various points of measured thrust normalized by division of the maximum thrust available at

[1] Positive z-Axis direction is downward, thus negative vertical airspeeds represent climbing.

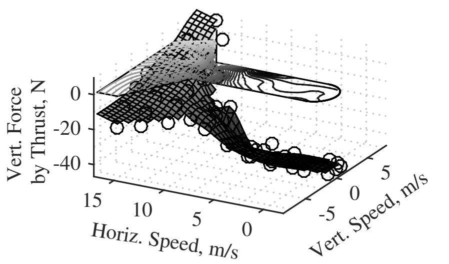
[2] The orientation of the z-axis is downward, thus the force is negative.



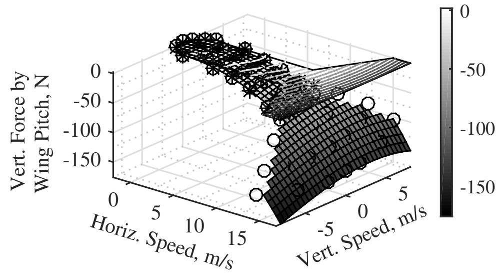
(a) Rolling Moment Caused by Ailerons



(b) Yawing Moment Caused by Ailerons



(c) Vertical Force Caused by Thrust



(d) Vertical Force Caused by Wing Pitch

Figure 6: Exemplary Effectivenesses

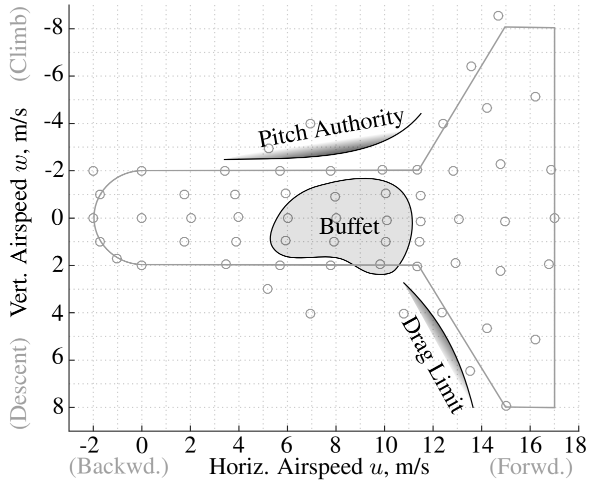


Figure 7: Performance Limitations

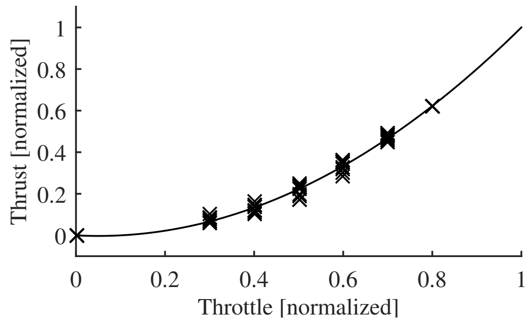


Figure 8: Thrust Over Throttle Setting

the respective incident flow, as well as the plot of an approximation function. This normalized thrust does not show a significant dependency on airspeed and can be approximated with a quadratic function of throttle[3] (1). The superposition of deflections can be done in thrust domain were forces and moments vary linear with thrust. The throttle setting to deliver the commanded thrust is calculated subsequently.

$$f = 1{,}11d^2 + 0{,}11d \quad (1)$$

Additionally a correction of battery voltage has to be applied to assure the same engine rotation speed at a given throttle setting and incident flow at non reference battery voltage. The thrust delivered by an engine and propeller has been measured over a variation of incident flow (airspeed and angle of incident), throttle setting and battery voltage. The thrust delivered at reference voltage can be determined and the necessary throttle setting can be calculated to deliver the same amount of thrust at the actual battery voltage. The acquired data shows significant dependency of normalized thrust on battery voltage and minor dependency on total airspeed.

[3] [5] shows similar dependencies on propeller RPM.

5 Conclusion

This paper demonstrated a way to acquire the necessary data for a newly proposed flight controller by wind tunnel investigations. The controller and hence the investigations pay special attention to tiltwing specific flight mechanics and aerodynamical properties.

The measured data was analyzed and processed to characteristic maps with the flight envelope as domain. These maps describe trim control surface deflection and control surface effectiveness dependent on the trim state. Further discoveries include flight envelope boundaries due to buffeting in certain trim states, the maximum stationary descent rate as well as limitations due to pitch authority.

If similar investigations need to be conducted in the future it is worth noting that the number of measurements points can be reduced especially in wing borne flight without loss of relevant information. A change in aircraft configuration should be considered in further development in order to avoid drawbacks resulting from buffeting. A possible alternative would be a tiltwing aircraft with canards instead of a conventional tailplane to prevent the wake of the wing from hitting the horizontal tailplane.

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