Fullscale Windtunnel Investigation of Actuator Effectiveness during Stationary Flight within the Entire Flight Envelope of a Tiltwing MAV

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Abstract

The tiltwing aircraft developed by team MAVerix of RWTH Aachen University is intended to operate in a continuous range of horizontal velocities from hover to fixed wing flight. The design of a flight controller enabling stationary flight states within the entire transition flight envelope demands detailed knowledge of the aircraft's flight mechanics. Data to implement a feed forward controller for longitudinal actuator settings (tilt angle, thrust and elevator/tail thrust) to satisfy stationary operating points in all horizontal velocities of the transition are gained by a wind tunnel investigation in the presented approach. Furthermore, to perform attitude controller design, the effectiveness of all actuators is recorded to decouple the attitude controller from altering magnitudes and directions of the actuators effects during transition.

Nomenclature

L, D	Lift and drag of the entire aircraft
T	Thrust specified by index
U_∞	Freestream velocity
X, Z	forces in x- and z-direction
L	Rolling moment
M	Pitching moment
N	Yawing moment
q	Dynamic pressure
b	Halfspan of the wing
S_{Wi}	Wing surface
x, y, z	Axis in coordinate system specified by index
α	Angle of attack
η	Elevator deflection
η_p	Tail rotor pitch deflection
δ	Differential thrust
ξ	Aileron deflection
σ	Tilt angle

Indexes

w	Weighing scale coordinate system
a	Aerodynamic coordinate system
f	Body fixed coordinate system
g	Earth coordinate system
Main	Main propulsion system
Tail	Tail rotor

1 Introduction

Team MAVerix is a student team from RWTH Aachen University participating in the outdoor-challenge of the International Micro Air Vehicle conference and competition (IMAV) since 2011. With respect to various mission challenges, the contestant Micro Air Vehicle (MAV) was designed as a tiltwing aircraft. In the course of past competitions, it was not possible to make use of the tiltwings full flight performance potential, due to deficiencies in attitude control. The MAV was not able to perform transition from hover to purely aerodynamic flight reliably. Control deviation due to unknown and therefore unconsidered coupling in actuator effectiveness was identified as one of the main reasons for this issue. Thus, an attitude controller including explicit decoupling of actuator effectiveness was designed. To gain the required understanding of actuator effectiveness for all stationary flight states, a full-scale windtunnel investigation was carried out.

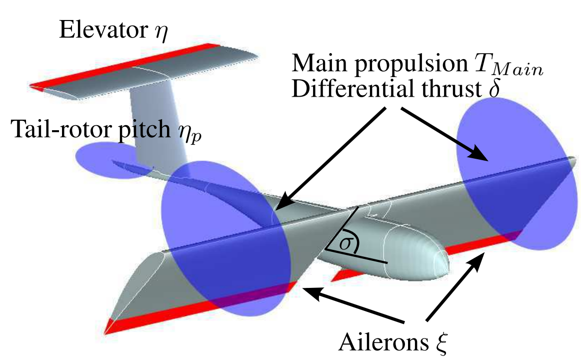

Figure 1: MAVerix with actuators

This contribution presents the corresponding windtunnel

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setup as well as selected results on actuator effectiveness. As a prerequisite for this investigation, actuator deflections for trimmed stationary flight within the entire flight envelope were measured and will also be presented.

2 TILTWING AIRCRAFT

The tiltwing configuration forms a combination of two different concepts of aircraft that allows stationary flight in a wide range of velocities. The advantages of a rotary-wing and a fixed-wing configuration are joined to perform energy efficient high speed flight in combination with vertical take-off and landing (VTOL) capabilities. The propulsion system is fixed to the wing so that the ailerons stay in slipstream of the propeller. For VTOL and hovering the wing is rotated and the propulsion system produces the lift. To perform high speed flight efficiently, lift is generated by the wing in fixed-wing mode.

2.1 *Specification of examined MAV*

The MAV with a wingspan of 0.96 m and a wing area of 0.24 m has a mass of ≈ 1.7 kg. The main propulsion system consists of two counter rotating brushless electric motors. The MAV is powered by a 4-cell lithium polymer battery. The ailerons extend over the complete size of the wingspan to use most of the slipstream. The MAV is equipped with a horizontal tail rotor to balance the pitching moment. The thrust of the tail rotor is varied by changing the pitch angle of the rotor blades while the rotational speed stays constantly at 7300 RPM. For reasons of simplification the rudder was omitted. In Figure 1 the actuators of the MAV are displayed.

2.2 *Flight mechanics*

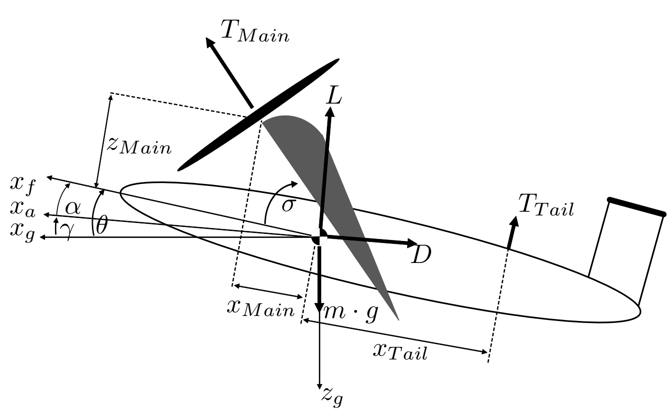

Figure 2: Forces and moments in longitudinal motion

Regarding flight velocity, the entire flight envelope of the tiltwing can be divided into three regions. While the pure aerodynamic flight and hover configurations form the border areas of the flight envelope, a third configuration, the transition, covers all flight states in-between.

The fixed-wing configuration is characterised by a fixed horizontal wing (tilt angle σ=0, compare figure 2) and well-known flight mechanics. Ailerons induce a rolling-, rudder (in our special case a differential thrust, compare figure 1) induce a yawing- and elevators induce pitching moments.

In hover configuration the wing is fixed in a vertical position. Flight mechanics can be compared to some extent to multicopter flight mechanics. Differences can be found for example in steering of yawing moment by deflection of the ailerons in the slipstream of the main propulsion system.

The transition is the phase in-between hover and aerodynamic flight. Depending on the tilt angle, differential thrust ΔT_{Main} of the main propulsion system as well as the ailerons ξ cause a combination of a rolling and a yawing moment. Differential thrust produces a rolling moment in hover and a yawing moment in aerodynamic flight. Analogous, as the ailerons ξ stay in the slipstream, they produce a yawing moment in hover and a rolling moment in aerodynamic flight. Not only is the direction of the effect dependent on the tilt angle but also is the effects magnitude due to different dynamic pressure q associated with airflow velocities. A simplified description of yawing and rolling moments can be found in (1) and (2). The general sign convention, that an actuator deflection is defined as positive when producing a negative moment [1], cannot be satisfied with a tiltwing. The ailerons cause a positive yawing moment in hover.

$$\begin{aligned} L &= -2 \cdot q(U_\infty, T_{\mathrm{Main}}) \cdot \Delta C_A(\xi) \cdot S_{Wi} \cdot \frac{b}{2} \cdot \cos(\sigma) \\ &\quad -2 \cdot \Delta T_{\mathrm{Main}} \cdot y_{\mathrm{Main}} \cdot \sin(\sigma) \qquad (1) \end{aligned}$$

$$\begin{aligned} N &= -2 \cdot \Delta T_{\mathrm{Main}} \cdot y_{\mathrm{Main}} \cdot \cos(\sigma) \\ &\quad + 2 \cdot q(U_\infty, T_{\mathrm{Main}}) \cdot \Delta C_A(\xi) \cdot S_{Wi} \cdot \frac{b}{2} \cdot \sin(\sigma) \qquad (2) \end{aligned}$$

In summary, with regard to the feedback control problem, it can be stated that the lateral steering during the transition flight state is heavily coupled.

Also the elevators effect depends on airflow velocity. For small forward velocities the elevator does not produce enough effect to balance the pitching moment, therefore an additional force is required. Furthermore during transition nonlinear effects like stall and couplings can cause instabilities.

Because of these effects the transition is often performed as a single continuous process by tiltwing, tiltrotor or tail-sitter aircraft. Transition trajectories are developed to get from hover to aerodynamic flight in a time optimized way [2]. However, the advantage of a tiltwing configuration - a continuous velocity range - can only be used by satisfying stationary flight states in all horizontal velocities of the flight envelope [3].

For a stationary flight state during the transition the forces and moments of the longitudinal motion have to be in an equilibrium $X, Z, M \stackrel{!}{=} 0$. Hereafter this state is called an operating point. The main thrust of both motors is summed up to $T_{\text{Main}} = T_{\text{left}} + T_{\text{right}}$. The three equations in (3) depend on the tilt angle σ and were simplified for small angle of attack α and pitch angle θ. The acting forces and moments are considered in the body-fixed coordinate system as displayed in figure 2. With changing horizontal velocity and tilt angle the force balancing the weight is altered from thrust to aerodynamic lift.

$$
\begin{aligned}
\Sigma X_f &= T_{\text{Main}} \cdot \cos(\sigma) - D(U_\infty, \sigma, T_{\text{Main}}) \stackrel{!}{=} 0 \\
\Sigma Z_f &= -T_{\text{Main}} \cdot \sin(\sigma) - T_{\text{Tail}} + m \cdot g \\
&\quad -L(U_\infty, \sigma, T_{\text{Main}}) \stackrel{!}{=} 0 \qquad (3) \\
\Sigma M_f &= M_{Aero} + T_{\text{Main}} \cdot (\sin(\sigma) \cdot x_{\text{Main}} \\
&\quad - \cos(\sigma) \cdot z_{\text{Main}}) - T_{\text{Tail}} \cdot x_{\text{Tail}} \stackrel{!}{=} 0
\end{aligned}
$$

2.3 *Feedback Control*

Historically the transition has always been hard to control due to the instabilities and non-linearities[4]. Thanks to more complex control algorithms the transition is controllable today.

For the MAV tiltwing a unified linear controller was designed. The controller negates the distinction between the three regions hover, transition and aerodynamic flight. The transition is treated as the general case, aerodynamic flight and hover are only border cases of transition. To be able to satisfy stationary, trimmed flight in all velocities within the transition, stationary operating points have to be known. A mapping and feed forward control of the deflection of all actuators for stationary longitudinal motion for different horizontal velocities is planned.

The AVIGLE tiltwing [5] uses a controller adjusting the tilt angle depending on the desired horizontal velocity while the thrust is controlled by the altitude control. HARVee is a Tiltwing [6] performing controlled transition flight based on a linearized model, also using automatic tilt control only. A feed forward control of the thrust and the pitching moment depending on the horizontal speed for tiltwing aircraft cannot be found in the literature.

For a unified attitude controller design, an explicit compensation of different actuator couplings and actuators effectiveness is required. The decoupling by inverting the actuator effects is ideally done before control design [7]. Therefore the variation of the actuator effectiveness in different operating points has to be analysed. With the inversion of actuator effects the attitude controller is approximately not affected by couplings and variation of the actuators and can be designed based on several independent single input single output (SISO) systems.

3 Wind Tunnel Measurements

The variances and couplings during the transition are investigated in wind tunnel measurements. The required settings for the actuators of the longitudinal motion for reaching a stationary operating point for different horizontal velocities are investigated. At all operating points all actuators are varied to record their effects direction and magnitude.

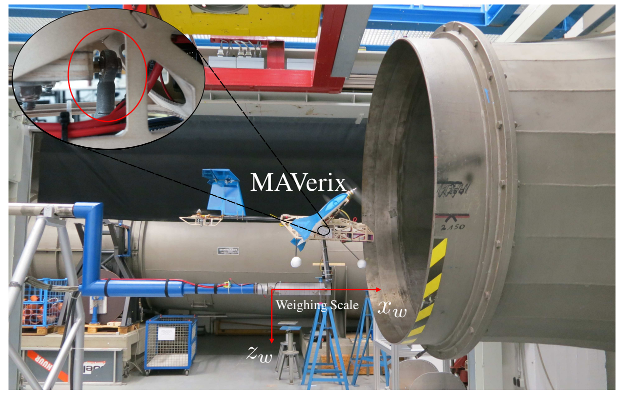

Figure 3: The measurement setup

The Institute of Flight System Dynamics operates a closed circuit wind tunnel with an open measurement section with a diameter of 1.5 m. The freestream velocity can be adjusted from $0 - 70$ m/s and was limited to 20 m/s during investigation. Due to the small size of the MAV a full scale airworthy measurement with simulated flight in the wind tunnel can be performed. The MAV is fixed on a weighing scale measuring resulting forces and moments. The setup is presented in figure 3, the fixed attachment can be seen as well as the ball joint as described in section 4.3. The pitch angle is set to zero as the airplane shall stay in horizontal position for all operating points of the transition. The freestream velocity correlates to the forward velocity of the MAV.

3.1 *Investigation of Operating Point Actuator Deflections*

Calibration of the weighing scale and reset to zero was done without the MAV installed on it. As a consequence, the weighing scale measured all forces including force of gravity, thus fulfilment of equations in (3) can easily be checked. By variation of the tilt angle σ, the thrust setting T_{Main}, deflections of the elevator η and variation of the vertical thrust T_{Tail} stationary operating points for all horizontal velocities of interest are found. The variations of the actuators are manually commanded by a remote control.

Figure 4 illustrates the procedure of reaching an operating point at an exemplary freestream velocity of 13 m/s by eliminating residual forces. The operating point found is tagged with a circle. Increase of the tilt angle causes a decrease of the force in z-direction and increasing thrust results in an increasing force in x-direction. With changing tilt angle the impact of changing thrust and tilt angle alters. This procedure is

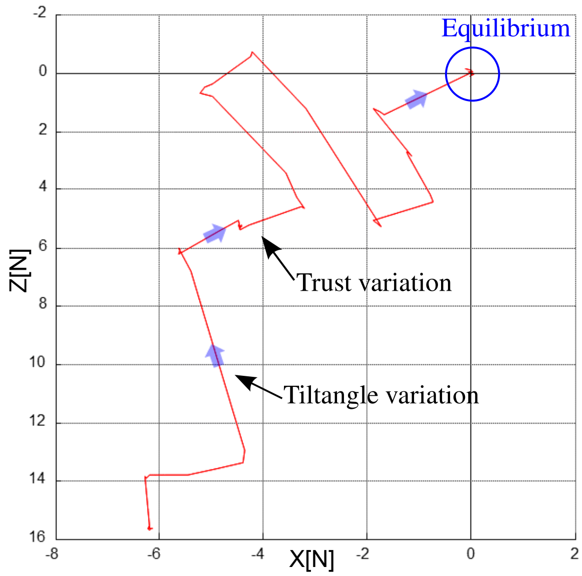

Figure 4: Process of balancing residual forces dependent on variation of tilt angle and thrust during exemplary investigation on one operating point

repeated for all velocity sample points within the flight envelope. Associated results are given in section 4.1

3.2 *Investigation of Actuator Effectiveness*

After finding an operating point for a particular velocity, the effectiveness in magnitude and direction of all actuators is measured. Dynamics of the actuators are not taken into account as only stationary measurements are recorded. As the attitude controller controls the tiltwing by generating rolling, pitching and yawing moments, the investigation focusses on the related actuators differential thrust, aileron deflection, elevator deflection and thrust variation of the tail rotor. These actuators are varied in two directions and two different amplitudes. For evaluation, the actuator effectiveness is normalized to unitary actuator deflection afterwards. The effectiveness of all actuators of interest is symmetric and assumed to be linear. Associated results are given in section 4.2

4 Results

At first the actuator deflections for longitudinal motion to obtain stationary operating points at different horizontal velocities are presented. The alteration of actuator effectiveness is discussed subsequently. All measurement plots are equipped with a compensating graph. The compensation function is given by a polynomial of different orders as a trade-off between smoothing and good reproduction of the measurement.

4.1 *Trim Point Actuator Deflections*

Figure 5 shows the operating point tilt angle as function of freestream velocity. The tilt angle decreases with increasing horizontal velocity. The entire range of possible tilt angles is not used, as a tilt angle of 90° produces a force in negative x-direction due to the propeller induced lift of the wing. On the one hand the tilt angle represents the direction of thrust, on the other hand the direction of the lift force. The magnitude of the lift increases with the increasing horizontal velocity. The trajectory is very similar to a simulated transition scheduling trajectory for the tiltwing *HARVee* [2].

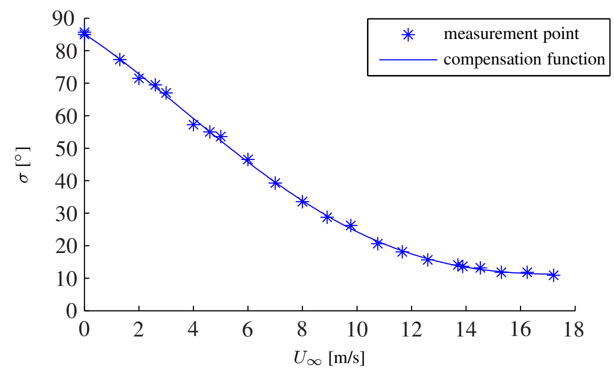

Figure 5: Operating point tilt angle σ for different horizontal velocities U_∞

In figure 6 the operating point thrust is given in terms of rotational speed of the main propellers. The input signal of the speed controllers of the main propulsion system was matched to a corresponding rotational speed during ground tests. The resulting deviations to reality because of incoming airflow are tolerated as this is only for overview. The operating point thrust provides the lifting force in hover and decreases while the lift is more and more produced by the wing with increasing horizontal velocity. A minimum of thrust is required at roughly 12 m/s while more thrust is necessary with increasing horizontal velocities due to growing drag.

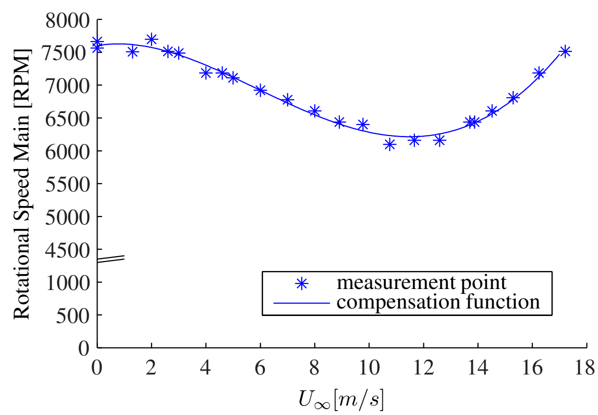

Figure 6: Operating point thrust of the main propulsion system for different horizontal velocities U_∞

Regarding elevator and tail rotor pitch deflections, the measurements in figure 7 show more variations than before. The variations can be explained by small possible movements around the pitching axis despite fixed mounting on the scale. For low horizontal velocities the pitching moment is produced by the tail rotor due to low effectiveness of the elevator. For velocities from 7 to 10 m/s elevator and tail rotor are used in combination. At a horizontal velocity of 10 m/s the effect of the elevator is big enough to operate the aircraft solely with the elevator. A provision in possible deflection for pitch control is available. Beyond this velocity the tail rotor is not necessary any more and is turned off.

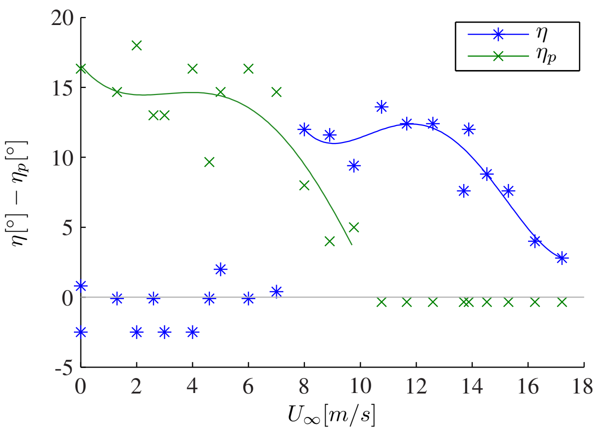

Figure 7: Operating point deflection of the elevator and tail rotor for different horizontal velocities U_∞

For constant power supply conditions the aircraft is powered by a mains power adapter during the wind tunnel measurements. This way the power consumption at different operating points can be analysed and is shown in figure 8. The main propulsion system represents the main power consumer. The shutdown of the tail rotor causes a drop in the trend of the power consumption. The most efficient and longest endurance flight can be accomplished by flying at a horizontal velocity of 12 m/s.

4.2 *Actuator Effectiveness*

In figure 9 effects of a positive, normalized differential thrust actuation on rolling and yawing moments for different operating points and their corresponding tilt angles are presented. Looking at the yawing and rolling moment as a vector, the vector rotates related with the tilt angle of the wing. This effect approves the approximation in (1) and (2), which are plotted in dashed lines. The thrust ΔT_{Main} is scaled to the un-interfered hover case of $\approx\ 10\ Nm$. Deviations from this theoretical approach might be caused by different horizontal velocities that change the inflow of the propellers and therefore the generated force variation. The main impact of this presumed effect can be seen in the yawing moment at fixed wing flight, which is in fact reduced to $\approx\ 6\ Nm$.

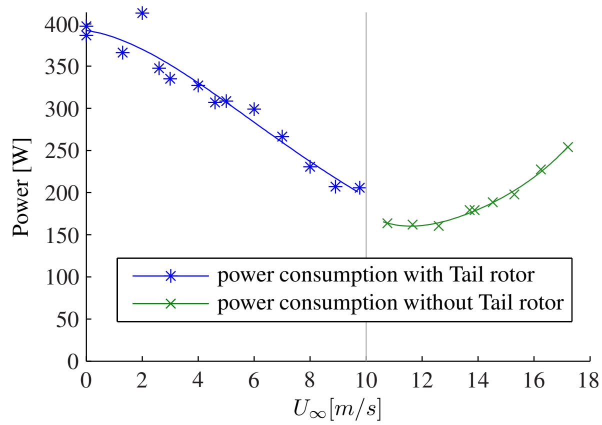

Figure 8: Power consumption at different operating points distinguishing between stopped and running tail rotor

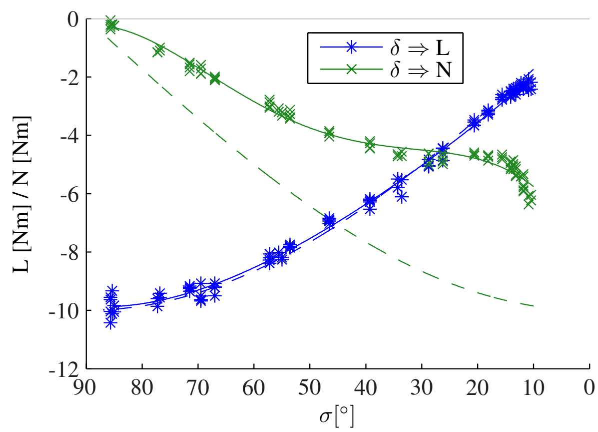

Figure 9: Effects of differential thrust in rolling and yawing moments at different tilt angles

In figure 10 the effects of a positive, normalized aileron deflection on rolling and yawing moments for different operating points and their corresponding tilt angles are presented. Similar to the differential thrusts effect, the direction of the aileron deflection effect changes because of the wings rotation. The magnitude of the effect is - as predicted in (1) and (2) - dependent on the dynamic pressure q which is influenced by the freestream velocity and the slipstream of the propulsion system. The approximations of these equations (plotted in dashed lines) are scaled to the hover case again. This leads to assumptions of the dynamic pressure of the propulsion system and the additional quasi-constant parameters. The dynamic pressure of the freestream velocity is matched to the current tilt angle according to figure 5. The neglected variation of the parameters over the change the inflow at different tilt angles and freestream velocities is one reason that leads to the deviation from the experimental results.

In figure 11 the effects of the elevator deflection and the

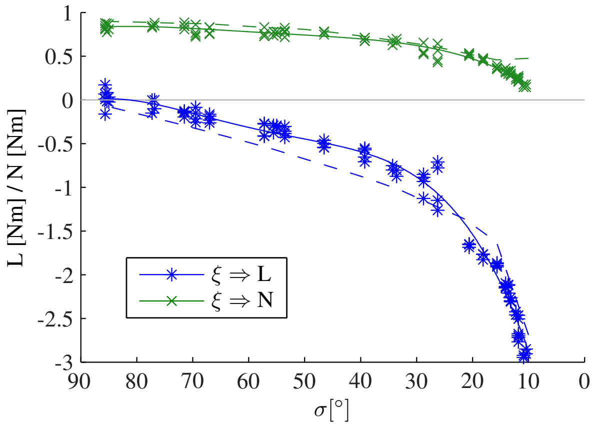

Figure 10: Effects of aileron deflection in rolling and yawing moments at different tilt angles

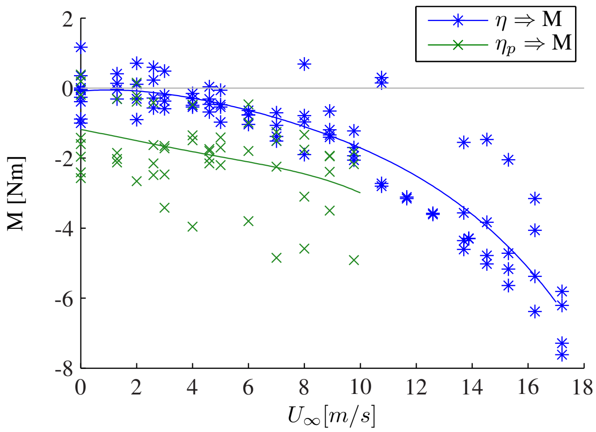

Figure 11: Effects of elevator deflection and tail rotor pitch deflection in pitching moment at different horizontal velocities

tail rotor pitch deflection on pitching moment are presented at different horizontal velocities. Please note, due to the fact that the tilt angle is not the main influence here, the abscissa indicates velocity, not tilt angle. The effect of the elevator is directly depending on the inflow velocity. Influences on the tail rotor effectiveness includes but is not limited to inflow velocity, the tilt angle and thrust of the main propulsion system. In total the influences cause an increasing effect with increasing horizontal velocity.

4.3 *Relevance of Results for Controller Design*

The wind tunnel investigation reveals the possibility to associate deflections for all actuators controlling the longitudinal motion to horizontal velocities. This can be used for a feed forward controller that steers all mentioned actuators in a way to obtain stationary flight for a given velocity.

The draft version of a feed forward control design for the MAV is realized in MATLAB/SIMULINK using *lookup-tables* to match the longitudinal actuator settings to a commanded horizontal velocity. Therefore the compensating functions approximating the wind tunnel data are discretized in steps of 0.5 m/s, in-between the sampling points the controller interpolates linearly.

A second wind tunnel measurement to validate the draft version of the feed forward controller was performed. Associated results can be seen in figure 12. During this measurement the aircraft was connected to the weighing scale by a ball joint, allowing rotational movements around the center of gravity of the aircraft. A detailed view of the ball joint is presented in figure 3. With different freestream velocities, while commanding a matching horizontal velocity, the remaining forces in x- and z-direction of the weighing scale were recorded. For all different horizontal velocities of the transition from $0\ m/s$ to $10.1\ m/s$ stationary flight states could successfully be obtained as the remaining forces only vary in a small range around zero.

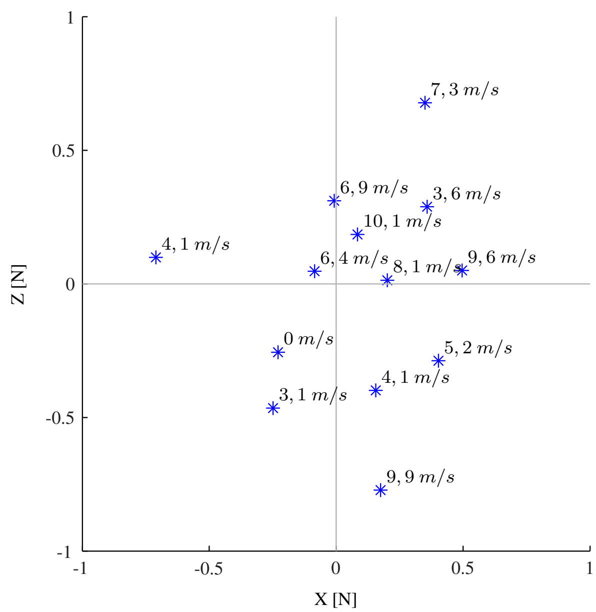

Figure 12: Remaining forces at the operating points at different horizontal velocities showing approximately zero mean residual distribution

Regarding attitude control the measured actuator effectiveness will help to decouple the steering of the tiltwing MAV. The altering of the actuators effectiveness is continuous over increasing tilt angles respectively increasing flight velocities. Additionally moments generated by ailerons, differential thrust and elevator are linearly independent at all operating points. This facts motivate an attitude controller including inversion of actuator effectiveness aiming at homogenisation of flight characteristics.

5 Conclusion

In this paper a wind tunnel investigation to gain insight into the flight mechanics of a tiltwing-aircraft during transition has been presented. Based on this investigation a draft version of a feed forward controller has been implemented. The draft version of the controller allows stationary trimmed flight within the entire flight envelope. The feed forward controller concept has successfully been proven in a second wind tunnel measurement for velocities from 0 m/s to 10 m/s. The aircraft is able to balance all forces and moments at any commanded horizontal velocity in this range. For pure aerodynamic flight with horizontal velocities from 10 m/s to 20 m/s the concept has to be proven in free flight experiments.

For future work the flight envelope can be extended towards small negative velocities during hover flight by making use of the entire tilt angle range up to $90°$.

To achieve identical flight characteristics within the complete transition, actuator effects have to be independent of a particular operating point. The alterations in direction and magnitude of the actuator effects dependent on the operating point have been recorded and analyzed. An inversion of these effects may provide an opportunity for designing an attitude controller consisting of several decoupled SISO controllers.

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