INVESTIGATION OF THE EFFECTS OF PROPELLER SLIPSTREAM AND TILT ANGLE ON THE CONTROL DEVICE EFFECTIVENESS OF A TILTWING AIRCRAFT

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Abstract

In order to fulfill its design missions, the unmanned tiltwing aerial vehicle AVIGLE has to be able to operate in a speed range from 0 to 40 m/s. Flight operations at speeds higher than 15 m/s are performed in a conventional configuration with the wing in horizontal position. To achieve stable flight conditions at lower velocities the main wing including propulsion is tilted upwards, so that a part of the engine thrust is added to the lift force. This influences the aircraft geometry, which means that the flow conditions at the different control devices change significantly, thus altering their effectiveness. Furthermore, the huge overlap between wing and propeller disc leads to the fact, that a change in thrust settings also notably influences the effectiveness of the ailerons and partly of elevator and rudder. In order to gain better understanding of the aircraft's flight dynamics, those effects were analyzed using wind tunnel investigations. The resulting aerodynamic database was then integrated in a 6-dof simulation, which is used for control system design and system validation.

1. INTRODUCTION

AVIGLE is a research project, which is funded by the European Union and the German federal state of Nord-Rhine Westphalia. It aims at the development of an unmanned multi-purpose flight platform. The planned mission scenarios include collecting visual data for the development of three dimensional object models as well as building ad-hoc on demand radio networks to provide additional mobile radio communication capabilities in the case of natural disasters or during mass rallies. In both cases deployment of the UAVs in self-organizing swarms is planned. Further information on the mission scenarios including an overview of the complete system can be found in [1].

The main task of the Institute of Flight System Dynamics within the AVIGLE project is the development of the flight platform and its control system. The selection of a tiltwing configuration was driven by specific requirements resulting from the different AVIGLE mission scenarios. Those were amongst others a vertical take-off and landing capability, a 0-40 m/s speed range with the capability of steady-state flight at all speeds, high agility and precise maneuverability. Further details on the design process are given in [2] and [3].

In this contribution the results of the recent wind tunnel test campaign with a semi scaled model of the AVIGLE tiltwing is presented. The campaign was carried out with two main purposes:

1) Gaining a better understanding of the influence of tilt angle and propeller slipstream on control device effectiveness.
2) Identification of the aircraft aerodynamics and creation of an aerodynamic coefficient database for implementation in a 6-dof simulation, which is used for the control system design and for system validation.

The aerodynamic data set has to fulfill certain requirements in order to be successfully integrated in the simulation framework. Those are presented in Section 3. Before that, in Section 2, a short overview on the specifics of tiltwings and of the AVIGLE aircraft in particular is given. The experimental setup used for the wind tunnel measurements is described in Section 4 and the results of the campaign are discussed in Section 5.

2. TILTWING

The concept of the tiltwing combines the vertical flight and hovering capabilities of a rotorcraft with the efficiency in horizontal flight of a fixed-wing aircraft and is therefore very flexible at accomplishing different missions. This is facilitated by a tilt mechanism, which allows the main wing including the propulsion system to be rotated about its lateral axis up to an angle of 90° to the longitudinal axis thus adapting the aircraft configuration to the current task. The higher degree of flexibility comes at the price of a higher complexity of the control systems and non-optimal performance in the different flight phases. One example of the latter is the necessary use of a hybrid type of propeller blades, which have to be compromised for both vertical and horizontal flight.

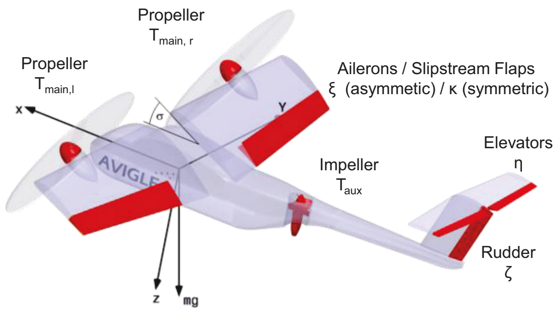

FIG. 1. AVIGLE control devices

The AVIGLE aircraft differs from other tiltwings, because of the requirement for steady-state trimmed flight at low speeds, below aerodynamic stall. In order to achieve controllability at these speeds the aircraft design includes large ailerons (FIG. 1), which are situated in the main engines' propeller slipstream and can therefore be effective even in the case of low dynamic pressure at low horizontal velocities. The ailerons can be deflected symmetrically for pitch and lift/drag control, thereby acting as slipstream flaps, as well as asymmetrically for roll and yaw control. Additional pitch control for vertical and low speed operations is delivered by an impeller, which is installed in the tail boom. Roll control in vertical flight is achieved through differential thrust on the main engines, which are equipped with propellers of 0.7m diameter and collective blade pitch control devices. The propellers cover about 2/3 of the wingspan, thereby influencing significantly the flow at the wing. An overview of the basic aircraft parameters is given in TAB. 1.

Parameter	Value
Wing span	2 m
Propeller Diameter	0.7 m
MTOW	10 kg
Maximum Speed	40 m/s
Design Speed	15 m/s
Minimum Speed	0 m/s (hover)

TAB 1. Basic AVIGLE tiltwing aircraft parameters

3. MODELLING AND SIMULATION

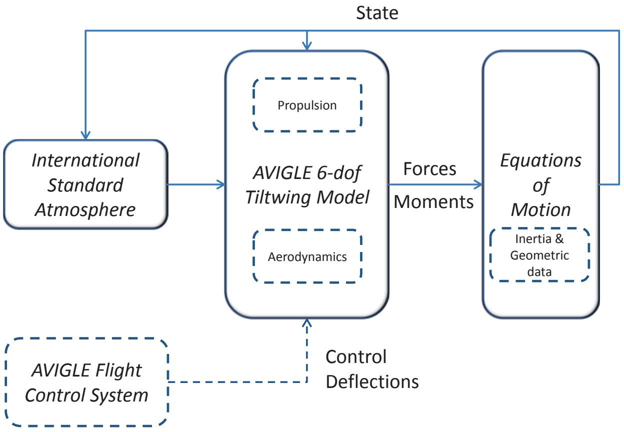

FIG. 2. AVIGLE Simulation Environment

A crucial part of the development of an UAV is the control system design. For this reason a simulation of the AVIGLE aircraft was built on top of an in-house developed generic 6-dof simulation, which was extended by the specific aspects of a tiltwing. At its top level the simulation model can be subdivided in the environment model, containing an implementation of the ISA standard atmospheric model, the aircraft model and a subsystem where the equations of motion for a flat earth are evaluated (as shown in FIG. 2). In this contribution the focus lies on measuring and modeling the acting forces and moments due to control device deflections and implementing them in the aircraft model.

3.1. Aircraft Model Structure

The forces and moments, which act on an aircraft, originate from three different sources:

1) Gravity
2) Propulsion
3) Aerodynamics

Gravitational forces are constant due to an all-electric energy supply system and will not be discussed further. The propulsion system model is simplified by a linear thrust model, driven by the throttle command, which is sufficient for a basic design of the control system.

The aerodynamics of the aircraft is modeled using static dimensionless coefficients like the pitching moment coefficient (Eq. (1)).

$$(1) \quad C_m = \frac{M}{qSl_\mu}$$

The coefficients can be obtained by numerical means or by direct identification on the aircraft model. It has been determined during the design process that using handbook methods and the available numerical programs is not sufficient to satisfactory describe the complex flight dynamics of the tiltwing. Therefore a series of wind tunnel tests for aerodynamic identification were conducted. In order to obtain wind tunnel data suitable for simulation integration, all relevant flight conditions have to be accounted for and measured. This means testing all possible geometric configurations at different free stream speeds. As the influence of the Reynolds number on the aerodynamic coefficients is small (but not negligible), measurements can be conducted at several characteristic velocities describing the trim points of the aircraft. In the case of a conventional fixed-wing airframe this usually leads to three-dimensional lookup tables for the aerodynamic coefficients depending on the angle of attack α, the sideslip angle β, and the relevant control device deflection. For example the pitching moment coefficient depends primarily on the elevator deflection η (Eq. (2)).

$$(2) \quad C_m = f(\alpha, \beta, \eta)$$

As described in the following section the tiltwing architecture poses some challenges to a successful identification, as the number of possible geometric configurations and working points of the aircraft is significantly increased. Furthermore additional parameters that influence the aerodynamic coefficients have to be considered.

3.2. Tiltwing Specific Considerations

There are several factors, which make the aerodynamics of a tiltwing more complex than those of a conventional fixed-wing aircraft. First, the rotation of the main wing leads to a significant change in the aircraft's geometry and thus of the aerodynamic coefficients of the different flight conditions. Hence, measurements have to be repeated over the entire tilt angle range σ leading to an additional dimension in the coefficient lookup tables and a high increase in the required wind tunnel time.

A tiltwing can operate at a large variety of forward speeds, thus posing the question at which free stream velocity (and Reynolds number) to conduct the measurements. Since steady-state flight at any tilt angle is desired, it can be argued that flight will always take place at a velocity near the trim velocity for the given tilt angle and so these velocities and respectively Reynolds numbers should be selected for the wind tunnel investigations. TAB. 2 shows the applied correlation between wing incidence angle σ and forward velocity for the transition process of the tilt-wing aircraft.

σ [°]	0-20	25	30-45	50-55	60-85[1]
V [m/s]	15	12.5	10	7.5	5

TAB 2. Correlation between free stream velocity and tilt angle during transition.

The trim speeds were approximately determined using previously identified lift/drag data [3] combined with thrust measurements of the propulsion system. The trim points were calculated for all tilt angles in 5°-steps and were verified in the wind tunnel prior to conducting the measurements presented here.

One additional challenge of a tiltwing design results from the big overlap between propeller disc and wing, resulting in significantly changed flow characteristics compared to a wing in free flow. The engine thrust influences the flow velocity and thus the dynamic pressure, as well as the angle of attack of the wing. The ailerons are also affected by the modified flow and even the elevator and rudder effectiveness is changing at certain combinations of thrust and tilt angle. Hence, to build a realistic simulation the aerodynamic coefficients have to be measured at different thrust values, thus increasing the dimensions of the lookup tables to five. For example the dependencies for the pitching moment coefficient are given in Eq. (3), whereas κ is used to denote control deflections in general.

$$C_m = f(\alpha, \beta, \kappa, \sigma, T) \tag{3}$$

In order to gain a better understanding of the interaction between slipstream and wing, respectively control devices, a method to separately determine purely aerodynamic and slipstream induced forces and moments, as shown in Eq. (4), is useful. Such a method is also important for a correct simulation of the flight dynamics in hovering flight, where only slipstream induced forces act on the aircraft.

$$C_m = C_{m,aero}(\alpha, \beta, \kappa, \sigma) + C_{m,i}(\alpha, \beta, \kappa, \sigma, T) \tag{4}$$

By conducting measurements on the airframe with an inactive propulsion system and by conducting additional measurements on the engines alone, a separation of aerodynamic and thrust effects is possible. The method is described in detail in Section 4.3.

A tiltwing can maneuver forwards and backwards as well as up and down and even sideways, so flight with all conceivable directions of inflow is possible. This means that for a complete simulation the development of separate aerodynamic databases for each flight direction is required. The most relevant flight case for normal operation is the forward flight, so the identification focus is put onto this configuration. It is assumed, that movement in all other directions occurs at low airspeeds, so the resulting aerodynamic forces and moments are small.

4. WIND TUNNEL INVESTIGATIONS

All presented investigations were conducted in the wind tunnel of the Institute of Flight System Dynamics of RWTH Aachen University. It has a closed circuit with an open measurement section of 1.5 m in diameter, allowing the identification of models with dimensions of up to 1 m wing span. The free stream velocity can be adjusted between 0 and 70 m/s and the different forces and moments acting on a model are determined by using a variety of balances with strain gauges.

4.1. Wind Tunnel Model

Because of the restrictions posed by the size of the wind tunnel measurement section, a semi-scaled model of the AVIGLE UAV (as depicted in FIG. 3) was investigated. In order to ensure Reynolds similarity, the free stream velocity has to be twice the corresponding free flight velocity of the original model, which was given in TAB. 2. For a correct determination of the slipstream-wing interaction, the propellers were scaled along with the model leading to the necessity to use different engines for the wind tunnel model. Semi scaling the model and doubling the free stream velocity leads to an unchanged drag force, so in order to obtain the same trim states the engines have to provide the same thrust levels as for the original model.

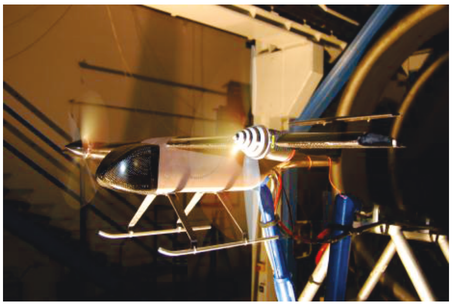

FIG. 3. Wind tunnel model

The control devices (elevator, rudder and ailerons) as well as the engine thrust settings can all be manipulated via a radio control link. The incidence angle of the wing of the scaled model can be adjusted in 5°-steps.

4.2. Experimental Setup

The most important aspect of the wind tunnel campaign is to deliver separate coefficients for purely aerodynamic and slipstream induced forces and moments. To enable this, three separate experiment series were conducted.

4.2.1. Identification of the Propulsion System

First of all the characteristics of the engines that are installed on the wind tunnel model have to be identified. To accomplish this, a single motor is mounted on a balance and the thrust in direction of the motor axis is measured for flow incidence angles from 0 to 90° covering all wing tilt positions.

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[1] The engines have an installation angle of 4°, therefore vertical flight is assumed to take place at a tilt angle of 85°.

From the acquired data the engine control settings for reaching a certain thrust level at all incidence angles can be calculated. Those are needed for precise quantification of the propeller induced slipstream velocity, which is given in Eq. (5) under the assumption that the flow behind the propeller disc is fully contracted.

$$V_i = \sqrt{V_{\inf}^2 + \frac{2T}{\rho S}} - V_{\inf} \tag{5}$$

It should be kept in mind that this simplified relationship has been derived using momentum theory and that V_i is assumed to be aligned with the zero-lift direction of the wing thus neglecting the influence of inclined inflow at the propeller disc. This is acceptable as V_i is intended only for building a reference dynamic pressure for the calculation of the slipstream induced aerodynamic forces and moments in the simulation. The real influence of the inclined flow is incorporated in the measurement data, which depends on the tilt angle of the wing and therefore of the propeller.

4.2.2. Clean Configuration Identification

The second wind tunnel series involves the model in a “clean” configuration without propulsion. The measurements are conducted for all tilt angles and all control device deflections, again at the previously defined trimmed free stream velocities. The considered control device deflection ranges are shown in TAB 3. Measurements were taken in 4° steps.

ξ	κ	η	ζ
-16° / +16°	-16° / +16°	-20° / +20°	-20° / +20°

TAB 3. Measured control device deflections

By using this method the purely aerodynamic coefficients can be determined, so they can be later subtracted from the coefficients measured with propulsion, in order to determine the slipstream induced forces and moments.

4.2.3. Identification of Tiltwing Aerodynamics Including Propulsion System

In the last series the complete model with working engines was measured. As the flow configuration at the wing highly depends on the propeller induced slipstream velocity, which was shown to be proportional to the square root of the engine thrust, it is appropriate to use the thrust as an additional parameter. It should be kept in mind that the thrust is not directly proportional to the thrust setting, but depends on the propeller incidence angle and the free stream velocity. Hence, appropriate values for the thrust settings had to be derived from the propulsion measurement data in advance.

For each tilt angle three thrust values around the trimmed condition were measured, as those give a sufficient base for interpolation (and potentially extrapolation) in the simulation environment.

The coefficients, which are obtained through this measurement, contain the sum of the purely aerodynamic, slipstream induced and thrust forces. In order to separate those, further calculations as shown in Sec. 4.4 are required.

4.3. Data Processing

To determine the slipstream induced forces and moments the slipstream independent aerodynamic forces and thrust forces have to be subtracted from the data acquired from the measurement with propulsion. In addition to this, in order to further be able to use dimensionless coefficients, a new reference dynamic pressure was defined. This is required, as there is no inflow dynamic pressure present during hovering flight, whereas slipstream induced forces and moments exist and need be quantified. The new reference dynamic pressure is defined by the sum of free stream and propeller induced dynamic pressure (Eq. (6)).

$$q_{tot} = q_{\inf} + q_i = \frac{\rho}{2} V_{\inf}^2 + \frac{\rho}{2} V_i^2 \tag{6}$$

The coefficients of the slipstream induced forces and moments can now be calculated, as follows for the pitch moment:

$$C_{m,i} = \left(C_{m,tot} - C_{m,aero} - C_{m,T} \right) \cdot \frac{q_{\inf}}{q_{tot}} \tag{7}$$

Due to the lack of free stream dynamic pressure, no aerodynamic coefficients can be determined for hovering flight, but only directly measured forces and moments. Those are consolidated with the other measurements by means of Eq. (8).

$$C_{m,hover} = (M - M_T) \frac{1}{q_{tot} S l_\mu} \tag{8}$$

By relating all slipstream induced forces and moments to the total dynamic pressure a seamless transition between forward and hovering flight can be achieved in the simulation.

5. RESULTS

In this section the measured effectiveness of selected control devices is presented. First the influences of tilt angle and slipstream velocity are described and subsequently an analysis of the effects on the overall flight characteristics is given. For all graphs the coefficient at a control deflection of 0° is taken as a reference value. All results are given at an angle of attack of 5°, which is representative for horizontal flight.

It should be noted that all pictured aerodynamic coefficients are related to the free stream dynamic pressure in contrast to the method described in Sec. 4.4. The reason for this is the better representation of the magnitude of the induced forces and moments, which can be directly compared to the purely aerodynamic ones. Still, this representation has a disadvantage regarding the discontinuous free stream velocities at which measurements for different tilt angles were conducted (TAB. 2). According to Eq. (5) those lead to different induced velocities, when holding the thrust constant. Therefore it should be kept in mind that the slipstream induced aerodynamic coefficient variations will be different for changing free stream velocities. Keeping the thrust constant while lowering the free stream velocity results in a higher induced velocity. This leads to rising aerodynamic coefficients as those are referenced on the free stream dynamic pressure.

5.1. Elevator

The elevator has to provide pitch control in horizontal flight as well as during flight at small tilt angles. At high tilt angles during low speed maneuvering the elevator becomes ineffective due to low dynamic pressure. One important result of the presented measurements is the resulting definition of the exact range, in which the elevator can be used for pitch control during transition.

5.1.1. Tilt Angle Effects

FIG. 4 shows the effect of the tilt angle on the elevator effectiveness. It can be seen, that at an angle of attack α=5° the elevator retains its effectiveness up to a tilt angle of σ≈20°. Further tilting of the main wing leads to flow separation that influences the horizontal stabilizer and gradually reduces the effectiveness of the elevator. At tilt angles higher than σ≈55° the elevator is completely immersed in the separated flow region and cannot be used for pitch control. For higher aircraft angles of attack the curves of FIG. 4 are shifted to the left, so that loss of elevator effectiveness takes place at lower tilt angles.

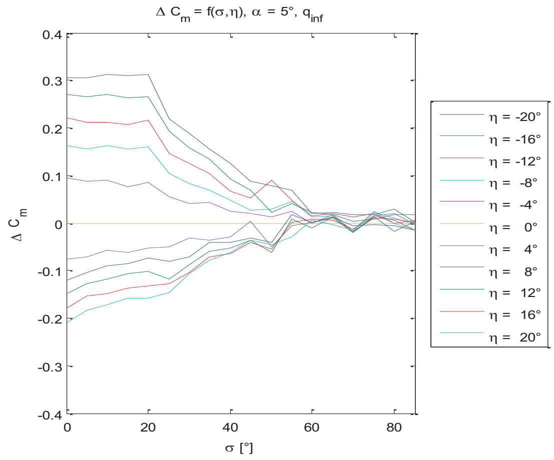

FIG. 4. Variation of the pitching moment coefficient due to elevator deflection at different tilt angles without thrust

5.1.2. Slipstream Effects

FIG. 5 shows the pitching moment coefficient variation due to elevator deflection with engines running at a throttle setting corresponding to 20N thrust at each engine. The thrust effect at low tilt angles is minimal, but the elevator effectiveness is substantially improved at tilt angles between 20° and 60°. It can be argued that the propeller slipstream increases the energy of the flow at the elevator, thereby enabling its usage at tilt angles of up to 45°. Further increase in tilt angle leads to unpredictable behavior, most likely due to separation vortices from the main wing striking the tail.

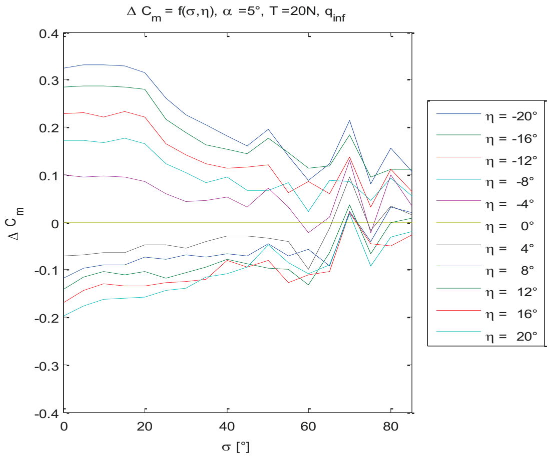

FIG. 5. Variation of the pitching moment coefficient due to elevator deflection at different tilt angles at 2x20N thrust

5.1.3. Analysis

It has been shown that the elevator remains completely effective for tilt angles of up to 20° at moderate angles of attack (<10°). At high angles of attack (20°) the elevator should not be used during transition[2], as its effectiveness quickly degrades. High thrust settings improve the performance, but as a precaution the aircraft control system is designed to use the elevator for tilt angles of up to 15° at moderate angles of attack. For higher values either the slipstream flaps or the impeller have to be used for pitch control.

5.2. Slipstream Flaps

The slipstream flaps (ailerons deflecting in the same direction) can theoretically be used for two purposes namely pitch control and lift control.

5.2.1. Tilt Angle Effects

As can be seen in FIG. 6 the pitching moment, which can be created by slipstream flap deflection, is insignificant at all tilt angles. The reason for this is that the application point of the additional lift is located close to the center of gravity, which results in a short lever arm. The additional lift due to slipstream flap deflection is depicted in FIG. 7. The values in horizontal flight are substantial, but quickly decrease as flow separation occurs at tilt angles approaching 40°. It can be seen that a positive flap deflection leads to a stall at lower tilt angles and therefore to no additional lift being produced at σ≈45°. In contrast to this downforces can be produced by a negative flap deflection up to σ≈60°. A control reversal effect can be observed at high tilt angles (σ>55°).

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[2] Transition is actually planned to take place at angles of attack near 0°.

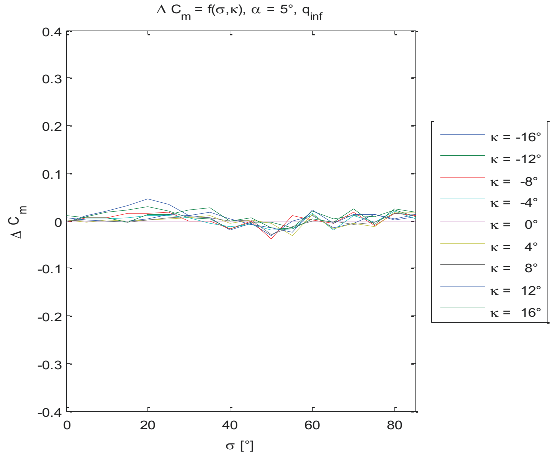

FIG. 6. Variation of the pitching moment coefficient due to slipstream flaps deflection at different tilt angles without thrust

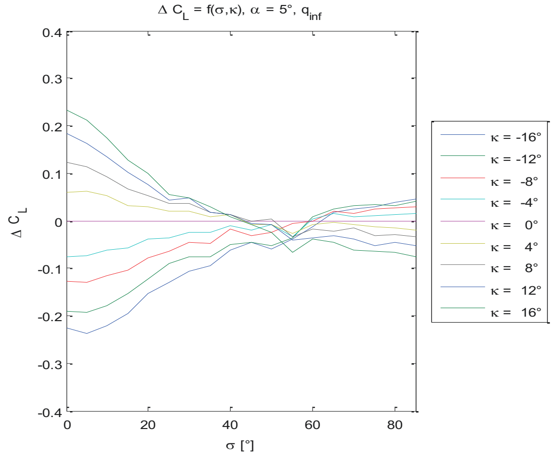

FIG. 7. Variation of the lift coefficient due to slipstream flaps deflection at different tilt angles without thrust

5.2.2. Slipstream Effects

It can be seen from FIG. 8 that even supported by the propeller slipstream the flaps provide very little pitching moment at low tilt angles. An increase in effectiveness can be observed for the tilt angle range between 20° and 70° however the behavior is erratic, so the flaps can hardly be used for pitch control.

The lift coefficients (FIG. 9) are bolstered due to the higher dynamic pressure at the wing. The graph clearly shows changes in slope direction at the points where the free stream velocity is modified, most notably at σ=25° and 60°. Supported by slipstream the flaps can deliver significant lift up to tilt angles of about 30° with stall once again occurring at 40°. The behavior at higher angles involves control reversal and is quite erratic, so usage of the flaps should be kept at minimum.

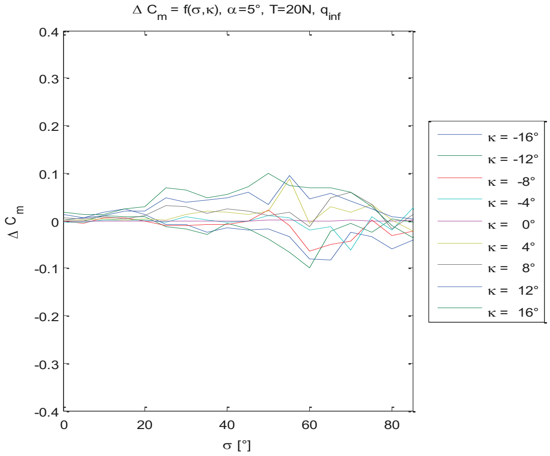

FIG. 8. Variation of the pitching moment coefficient due to slipstream flaps deflection at different tilt angles at 2x20N thrust

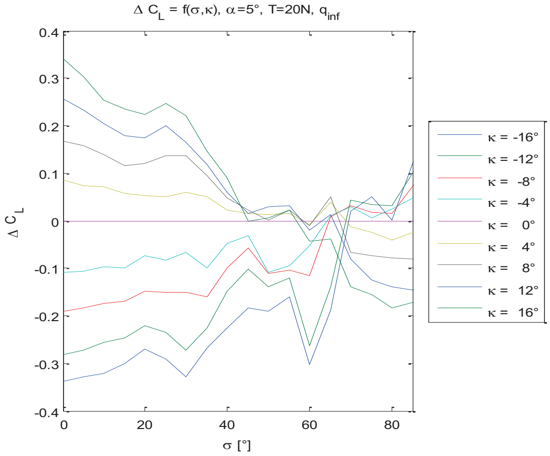

FIG. 9. Variation of the lift coefficient due to slipstream flaps deflection at different tilt angles at 2x20N thrust

5.2.3. Analysis

The gathered data reveals that the slipstream flaps cannot be used for pitch control for the AVIGLE tiltwing configuration, because the pressure point of the wing is located near the center of gravity. This however allows the usage of the flaps as direct lift devices, thus enabling the aircraft to change altitude quickly in horizontal flight without any changes in pitch attitude. Still, an appropriate controller compensating the higher drag with thrust from the main engines has to be designed.

One fact that was not accounted for is that the center of gravity notably shifts during the tilting process due to the engines being moved upwards and backwards. This effect is actually desired and required, because of the fact that the center of gravity has to be behind the main thrust application point in order to enable longitudinal trim with the help of the impeller in vertical flight mode. In contrast to this, the desired center of gravity position in horizontal flight is further forward, in order to achieve better static stability characteristics. The center of gravity shift can also be of advantage for the use of the slipstream flaps for pitch control as it provides a bigger lever arm at high tilt angles.

5.3. Ailerons

The ailerons are used for roll control during horizontal flight and for yaw control during vertical flight. Analyzing the coupling between roll and yaw during transition is an important aim of these investigations.

5.3.1. Tilt Angle Effects

The rolling and yawing moment coefficient variations due to aileron deflection without thrust are depicted in FIG. 10 and 11. Up to a tilt angle of 20° the ailerons gradually lose their effectiveness in roll and start generating a yawing moment. This effect results as the downwards deflected aileron produces more drag than the upward deflected one. Beyond σ≈15° flow separation occurs at high deflections at the lift producing wing[3] (the downforce producing wing is not affected), thereby reducing aileron effectiveness. At σ≈45° the lift producing aileron appears to be stalled to a state, where the weight of the corresponding wing equalizes the downforce at the other wing resulting in a zero roll moment. At the same time the stalled aileron still generates more drag, which leads to a corresponding yawing moment. An additional increase of the tilt angle stalls the downwards deflected aileron further leading to a complete roll control reversal. It can be observed that the yawing moment stays approximately constant in the tilt angle range between 30° and 60°. It even disappears when approaching σ=90°.

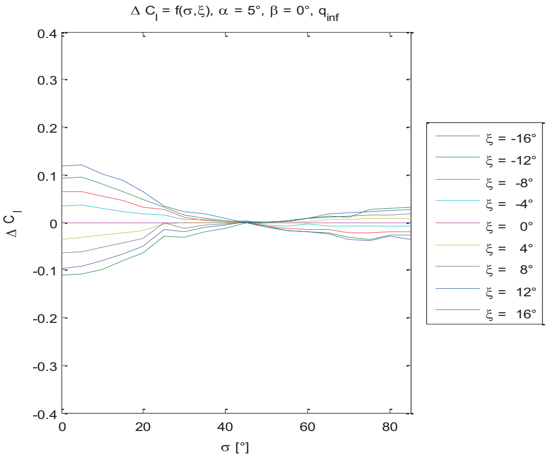

FIG. 10. Variation of the rolling moment coefficient due to aileron deflection at different tilt angles without thrust

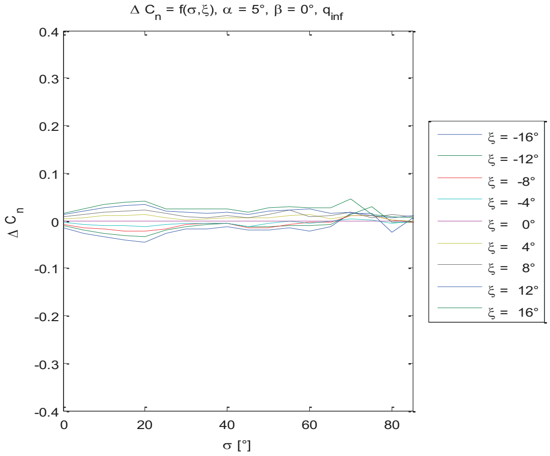

FIG. 11. Variation of the yawing moment coefficient due to aileron deflection at different tilt angles without thrust

5.3.2. Slipstream Effects

The propeller slipstream effects on the rolling and yawing moments due to aileron deflections are shown in FIG. 12 and 13. The higher velocity due to the slipstream delays the occurring stall at the wings and enables the ailerons to still be effective at tilt angles of about 30°. The control reversal is even further postponed to an angle of about 65°. The peak at σ=60° is the result of changing to a lower free stream velocity, as described in Sec. 5.

Furthermore, the slipstream significantly changes the disposition of the yawing moment characteristics. The higher dynamic pressure results in higher yawing moments up to σ≈30°. When further tilting the wing, the yawing moment coefficient remains relatively constant up to σ≈55°, analogous to the case without thrust, but at higher levels. At σ=60° once again the change in free stream velocity is made visible through distinct peaks in the curves. At higher tilt angles the ailerons gradually lose their effectiveness in yaw as they have to further rely only on the slipstream for providing dynamic pressure.

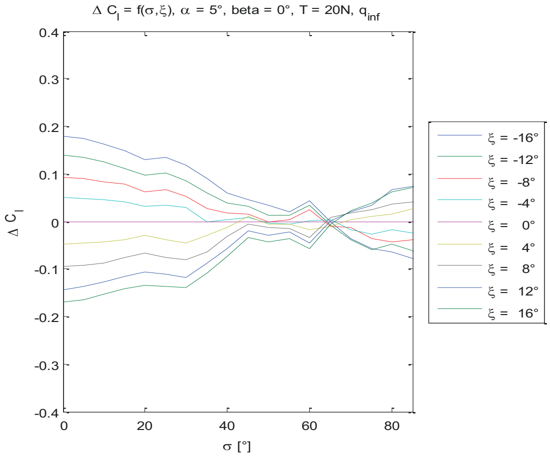

FIG. 12. Variation of the rolling moment coefficient due to aileron deflection at different tilt angles at 2x20N thrust

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[3] The term “lift producing wing” is used for the wing with the downwards deflected aileron. Naturally both wings produce lift, which can be increased or decreased by the aileron deflection. Analogous for “downforce producing wing”.

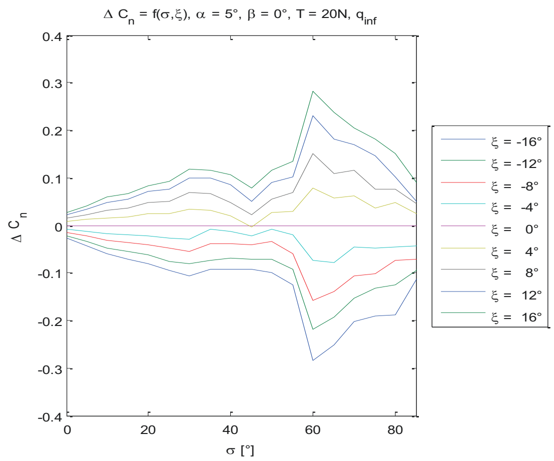

FIG. 13. Variation of the yawing moment coefficient due to aileron deflection at different tilt angles at 2x20N thrust

5.3.3. Analysis

The measurements show the coupling between roll and yaw for horizontal flight, which can be controlled by appropriate rudder deflections. In vertical flight mode or at very high tilt angles lateral control can be achieved by using differential thrust on the main engines for roll and aileron deflections for yaw control. However, providing sufficient lateral control during transition poses a challenge. Taking into account the additional flow velocity from the propeller slipstream the ailerons can provide roll control up to tilt angels of σ≈65° at high thrust settings. However, balancing the coupled yaw moments with the rudder becomes less feasible, because of decreasing dynamic pressure. Therefore achieving lateral control during transition and especially at tilt angles between 45° and 75° requires a dedicated control system, which coordinates rudder and aileron deflections as well as thrust differentiation at the same time.

6. CONCLUSION AND OUTLOOK

In this contribution results of the latest wind tunnel campaign dedicated to the AVIGLE project were presented. The tiltwing specific effects of the wing incidence angle and the propeller slipstream on the control device effectiveness were investigated. Moreover the allowable operating ranges of the control devices in the different flight modes were analyzed and determined.

It could be shown by wind tunnel tests that slipstream flaps can only be used for pitch control if the center of gravity is significantly shifted during transition. However slipstream flaps can be used for lift control in horizontal flight. Due to the coupling between roll and yaw and the required use of three different control devices (rudder, ailerons and differential thrust), lateral control during transition will require a tiltwing specific control system.

The data gathered during this test campaign, will be integrated into the simulation model in order to design the flight control system and finally to validate the aircraft concept. Based on the results of the wind tunnel tests free flight test for determination of the dynamic characteristics of the AVIGLE tiltwing will be conducted in the near future.

7. ACKNOWLEDGEMENT

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8. NOMENCLATURE AND ABBREVIATIONS

T	[N]	Thrust
M	[Nm]	Pitch moment
S	[m^2]	Wing reference area
l_μ	[m]	Mean aerodynamic chord
V	[m/s]	Velocity
q	[Pa]	Dynamic pressure
i	[°]	Motor installation angle
α	[°]	Angle of attack
β	[°]	Sideslip angle
σ	[°]	Tilt angle
η	[°]	Elevator deflection
ξ	[°]	Aileron deflection
κ	[°]	Slipstream flap deflection/control device deflection in general
ρ	[kg/m^3]	Density

i	Index: induced
aero	Index: aerodynamic
inf	Index: free stream
tot	Index: total
T	Index: Thrust

9. REFERENCES

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