On the Design of Hybrid Micro Air Vehicles for Multi-Tasking Missions

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***Abstract*—In order to achieve multi-tasking recognition missions, micro air vehicles may take advantage of the tilt-body concept which allows for hover and horizontal flight. This paper discusses some design and performance issues related to convertible micro air vehicles. First, a theoretical model is proposed to predict the performance of a proprotor throughout its flight regime (from 0° to 90°). It is compared to experimental results and used to enhance McCormick's model for calculating a propeller-wing interaction. The resulting proprotor is compared with a collective pitch-based propeller in terms of performance and control. Second, a generic propeller-wing configuration has been studied. A side-by-side comparison between experimental and numerical results is discussed. It shows that when the propeller is running, wing efficiency is greatly increased and equilibrium transition becomes possible. Third, a practical tilt-body configuration has been designed and wind-tunnel tested in order to demonstrate the benefit of tilt-body configurations for micro air vehicles recognition missions both in outdoor and indoor environments. Finally, a flight model and control laws for transition flight have been developed and applied to an existing flying prototype. The importance of fully equilibrium transition is demonstrated and ground effect in flight modes is discussed.**

Keywords—Micro air vehicle; convertible; tilt-body; proprotor

I. INTRODUCTION

The use of Micro Air Vehicles (MAVs) for indoor/outdoor recognition missions in complex urban environments requires the design of MAV configurations capable of both horizontal and vertical flights. End-users generally expect MAVs to complete a typical mission scenario such as: a. flying to a remote location, b. loitering and collecting sensor data for an extended period of time, c. hovering to identify targets, d. entering buildings, landing, and taking off, without human assistance. So far, conventional fixed wing MAV configurations have been appropriate to complete outdoor surveillance missions because they can easily cope with adverse wind conditions and provide a fairly good range as opposed to VTOL configurations. However, for practical applications, fixed-wing MAVs suffer from their intrinsic limitation to sustain low-speed or hover flight. On the other hand, conventional VTOL MAV configurations such as multirotor platforms offer the capability to persistently survey an area by hovering or by achieving a "perch-and-stare" approach. Yet, VTOL configurations usually have a limited endurance and fail to efficiently sustain high speed flight. Therefore, it is of interest to combine the fixed and rotary wing capabilities into a single convertible-rotor aircraft.

In order to achieve either translation flight or vertical flight, different options are available. One is to directly tilt the rotors or the wing located in the rotor slipstream such as in the V-22 "Osprey" configuration. The main drawback of the tilt-rotor concept is that in hover the propeller slipstream produces a downward force because of the propeller-wing interaction. Other options include tilt-wing configurations in which some portion of the wing rotates along with the rotor. By doing so, the downforce generated in hover is greatly reduced. As applied to MAVs, the *AVIGLE* developed at RWTH Aachen University (Fig. 1) is an example of such a concept which requires an additional rotor above the horizontal tail in order to control the pitching moment [1]. The advantage is that the fuselage remains horizontal throughout the flight. Both tilt-rotor and tilt-wing configurations are mechanically complex and involve moving parts which means weight penalty and fragility.

Fig. 1 – The *AVIGLE* micro air vehicle flight tested by RWTH Aachen University (2013).

Another approach consists of designing a fixed-wing configuration which can be tilted as a whole so as to perform hover flight in a "prop hanging" mode. Such a tilt-body concept has been around for over half a century with the famous Convair XFY-1 "Pogo" developed and flight tested in the 1950s as an example. A brief history of vertical/short takeoff and landing (V/STOL) developments is given by McCormick [2], and several articles in the literature are available on these types of aircraft [3–5].

In the field of mini-UAVs, such a tail-sitter configuration called "Vertigo" was developed and flown in 2006 at ISAE and further miniaturized in collaboration with the University of Arizona to provide the "*Mini-Vertigo*" (Fig. 2), a 30-cm span coaxial-rotor MAV capable of transition flight [6]. However, the coaxial rotor hollow shaft driving mechanism brings extra weight and represents a technological limitation to design smaller versions. Furthermore, because of its small wing aspect ratio, the *Mini-Vertigo* generates a fairly high induced drag in cruise conditions.

Fig. 2 – The *Mini-Vertigo* micro air vehicle flight tested by the University of Arizona (2007).

II. TILT-BODY MAV DESIGN ISSUES

In view of improving the aerodynamic efficiency in horizontal flight and simplifying the rotor mechanism, a new tilt-body configuration based on a bimotor flying wing, called *MAVion*, has been designed. The *MAVion* has been initially designed to be a reasonably efficient airplane, capable of flying outdoors and easy to replicate as opposed to tail-sitters with more complex design [7]. As an example of such tail-sitters, the *T-Wing* configuration developed at the University of Sidney should be mentioned since it combines in a single configuration two cross-wing configurations and a canard-type lifting fuselage (Fig. 3).

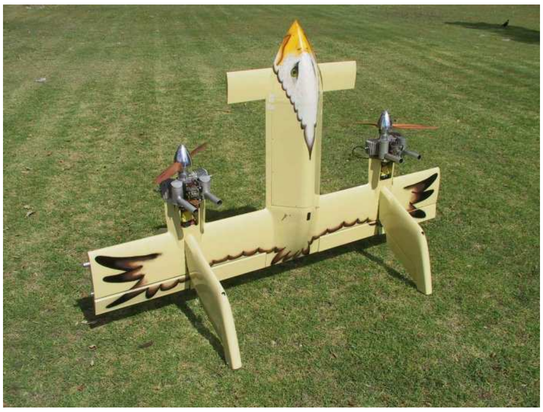

Fig. 3 – The *T-Wing* micro air vehicle flight tested by the University of Sidney (2002).

In addition to a simplified fabrication, another important design guideline has been to get rid of any moving parts with the exception of light control surfaces such as flaps or elevators. The reason is that moving a whole wing such as in the *AVIGLE* configuration or heavy components such as motors as in the case of the fixed-wing tilt-rotor *Skate* UAS from Aurora Flight Sciences (Fig. 4) may introduce some complexity in terms of control since the aircraft center of gravity is subject to change during transition flight. Also, controlling the aircraft by moving heavy components may limit the reaction time and degrade maneuverability.

Fig. 4 – The *Skate* micro air vehicle flight designed by Aurora Flight Sciences (2012).

The main design guidelines for the *MAVion* were fabrication simplicity and transition flight capacity. As opposed to a coaxial rotor, the use of tandem counter-rotating rotors in tractor configuration allows for an additional degree of freedom providing control in yaw [8]. Furthermore, by using two rotors in tractor configuration, the propeller slipstream may be significantly extended in the spanwise direction, which is consistent with the need for a higher wing aspect ratio. The aerodynamic efficiency of the *MAVion* elevators is guaranteed over the whole transition flight range since in hover, when the freestream flow is drastically decreased, the propeller slipstream maintains the elevator aerodynamic efficiency.

While in the *MAVion*, the proprotors constantly blow the elevators in order to provide control both in roll and yaw, in the quadrotor-biplane MAV designed at the University of Maryland [9], the fixed wings are not equipped with elevators

(Fig. 5). They only provide lift for horizontal flight. As a consequence, the airfoils do not need to have a positive pitching moment at the aerodynamic center. They can be taken from a family of low-Reynolds airfoils with high lift coefficients. However, longitudinal equilibrium of the aircraft in horizontal flight requires some differential throttle between the upper wing and the lower wing, since a positively cambered airfoil produces a negative pitching moment. Also, control of the aircraft is only achieved by adjusting the different motors rotation speeds.

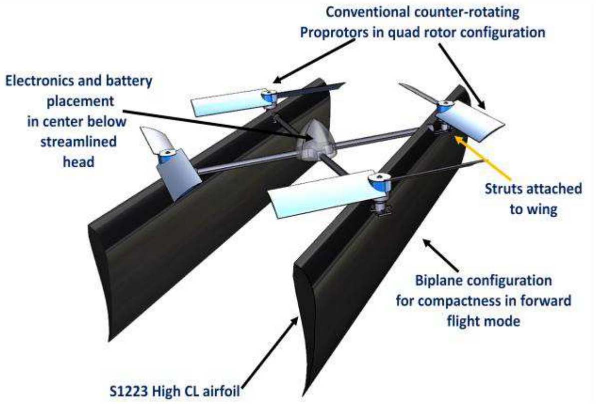

Fig. 5 – A tilt-body quadrotor-biplane micro air vehicle designed at the University of Maryland (2014).

Finally, the *MAVion* (Fig. 6) simply combines a fixed-wing airframe with tandem counter-rotating rotors. The direction of motor rotation has been chosen to counter wing tip vortices, which artificially increases the aspect ratio. It also provides a natural way to trigger banked turns since increasing the left motor speed would not only result in a right-turning moment in yaw but also in an induced right-turning rolling moment.

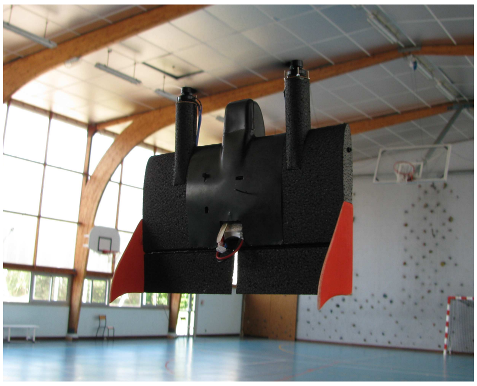

Fig. 6 – The *MAVion* micro air vehicle designed at ISAE.

In order to provide longitudinal static stability, a low-Reynolds airfoil MH45 designed by Martin Hepperle in 1990 has been selected. The typical span dimension is 40 cm which is considered as a good maximum dimension in order to perform building intrusion.

III. HYBRID ROLL & FLY VERSION

In view of extending the range of possible applications, a wheeled hybrid version of the aircraft, called "Roll & Fly" (Fig. 7), has also been developed to enable the *MAVion* to roll along the ground, walls, or ceilings, increasing its effectiveness in indoor settings. Adding wheels which freely rotate on either side of the aircraft also provide a natural way to land, turn motors off and take off again without human assistance since the center of gravity is located aft the wheels rotation center. For practical use, the “perch and stare” capability is very useful since it also corresponds to a way to provide acoustic covertness when needed. Another interesting feature provided by the use of free wheels is that a constant wall distance may easily be maintained while flying along a surface. That can be an advantage when monitoring some surface details for instance. Also, flying along walls may also provide some natural assistance to the operator, which can be particularly useful when exploring unknown environments.

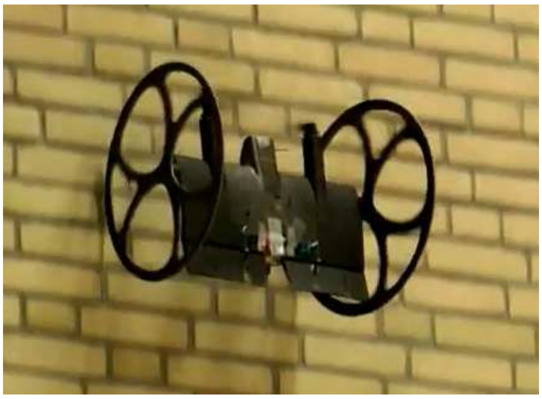

Fig. 7 – The hybrid wheeled-version of the *MAVion* called *Roll&Fly*.

The center of gravity being in front of the wing aerodynamic center, static stability is provided in horizontal flight. Consequently, a desirable order for the three centers are, from nose to tail: wheel rotation center, center of gravity, aerodynamic center.

The wheel diameter also provides natural protection to the proprotors in the event of collision. Using flexible wheels made of carbon rods for instance may provide some energy-absorbing capability which may increase the vehicle robustness against rough landings. It should be mentioned that wheels should be large enough to allow for a sufficient distance between the ground and the elevator trailing edge. If the elevators are too close to the ground, longitudinal control is difficult to achieve because the elevators are then located within a region of low dynamic pressure where the aerodynamic efficiency drops.

IV. PROPROTOR OPTIMIZATION

While several authors report data and models for propeller in yaw (up to 30°), few studies have investigated the problem of a propeller at very high angles of attack [10]. Tilt-rotor or tilt-body concepts require selecting a propeller which can equally perform for horizontal flight (in “propeller” mode) as well as in vertical flight (in “rotor” mode). The concept of “proprotor” has been introduced in order to design rotors which would give good performances in both configurations. In the case of the *MAVion*, horizontal cruise is performed at 16 m/s where the propeller thrust should be equal to 0.31N while hover requires a thrust of 1.6N. Generally, horizontal flight requires high-pitch blades while vertical flight requires low-pitch blades.

In the present study, three different proprotors have been compared: a. the APC 7x5 is a commercially available propeller designed for electric flight. It is a 17.78cm (7 in.) propeller which has been selected among various options because it provides good performances in hover and in cruise, b. an optimized propeller for cruise conditions, c. an optimized propeller for hover. Optimized proprotors have been obtained by minimizing the induced losses [11] and computed using QMIL developed at MIT by Mark Drela. The first result is that the hover optimized proprotor cannot meet the requirements of cruise flight conditions while the cruise optimized proprotor can still perform reasonably well in hover. Another result is that the APC 7x5 represents a good trade-off for a rigid proprotor as illustrated in Table 1. The expected endurance is 52 min. in cruise and 25 min. in hover while the cruise optimized proprotor can achieve 73 min. in cruise and 15 min. in hover. Again, although the hover optimized can provide longer endurance in hover (45 min.) it is not capable of providing the necessary thrust for a horizontal flight at 16 m/s, even by using unlimited motor power.

TABLE I. COMPARISON OF PROPROTORS EFFICIENCIES

Propeller	Pitch	Cruise			Hover		
		B	η_{Total}	End.	B	η_{Total}	End.
APC 07x05 Theoretical	Fixed	-	41%	52	-	32%	25
APC 07x05 Theoretical	Variable	7	43%	57	-10	56%	45
Cruise optimized (cambered)	Fixed	-	57%	73	-	26%	15
Cruise optimized (cambered)	Variable	-6	59%	74	-26	39%	28
Hover optimized (cambered)	Fixed	-	-	-	-	56%	45
Hover optimized (cambered)	Variable	~25	~30%	~18	0	56%	45

Because the pitch blade of optimized proprotors may vary between hover and cruise, it is of interest to consider mounting rigid blades on a collective pitch mechanism. Each of the three blades under consideration has been computed with adjusted pitch angles so that endurance may be maximized in both cruise and hover. The result (Table 1) shows that the hover optimized proprotor can now reasonably perform in cruise conditions but with very limited endurance as compared to the cruise optimized proprotor mounted on a collective-pitch mechanism. In the case of the cruise optimized proprotor, the collective-pitch mechanism allows for doubling the endurance in hover. The APC 7x5 mounted on a collective pitch device can also drastically increase the aircraft endurance in hover from 25 to 45 min.

Finally, using a collective-pitch mechanism on an existing vehicle may be an interesting design option. On the one hand, it brings extra weight and requires an additional servo for each motor. On the other hand, it may significantly improve the endurance and the control qualities in hover because of shorter response times as compared to speed controllers. This can be useful in practice when hovering in gusty conditions.

V. WIND TUNNEL CAMPAIGN

The propeller-wing interaction has been studied by several authors [11-12] while few studies have been conducted to actually provide a full model of the aircraft in transition flight. It is the purpose of the present study to provide a full aircraft model for transition flight.

There is not a single way to transition between horizontal and vertical flight modes. One can either perform transition dynamically by following a nose-up trajectory resulting in a low-incidence but high pitch angle variation until the vehicle reaches a vertical position at zero ground speed (Fig. 8). That strategy is only possible when there is no wind.

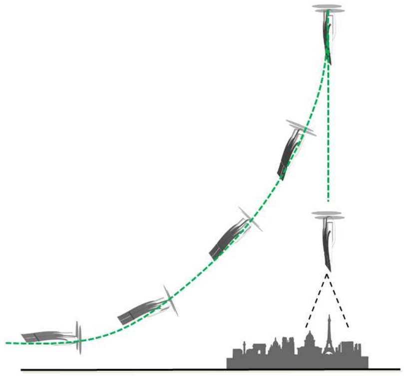

Fig. 8 – Low-incidence dynamic transition.

In windy conditions however, an alternative strategy is required. It consists of progressively tilting the vehicle until it reaches an equilibrium state which corresponds to a zero ground speed under the actual wind speed conditions (Fig. 9).

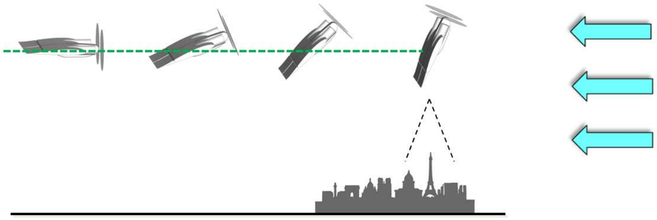

Fig. 9 – High-incidence equilibrium transition.

Because of its practical interest, the intent of the current study is to explore equilibrium transition, defined here as maintaining the summation of the steady state forces and moments close to zero. This results in an energy efficient change between flight modes with no gain or loss of altitude.

The experiments were ran at the MAV closed-loop wind tunnel located at ISAE and capable of delivering low Reynolds stable and uniform flow at a wind velocity ranging from 2 to 25 m/s, thanks to its variable-pitch fan. The wind tunnel rectangular test section is 1.2 x 0.8 m with the largest dimension in the horizontal direction. The wind tunnel test section is 2.4m long which allows for wake analysis. The contraction ratio is 9:1 which allows for a reasonably low turbulence intensity level of about 0.3% at 10 m/s. The wind tunnel model is attached to the mounting setup through a 5-component internal balance which measures 2 force components perpendicular to the balance axis and 3 moment components. The missing axial component requires a change in the mounting system as illustrated in Fig. 10.

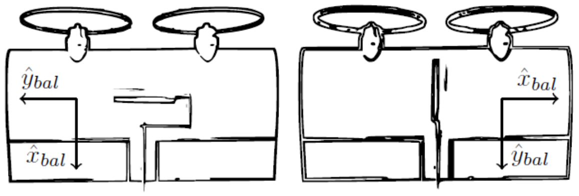

Fig. 10 – Two experimental setups with modified internal balance orientations.

It is equipped with a mounting system which can rotate from -90 to +90° in the horizontal direction and from -10 to +30° in the vertical direction. Finally, the sting-mounted experimental setup (Fig. 11) combined with the two internal balance orientations provides a full identification of the vehicle flight model, with angles of attack and sideslip angles ranging from 0 to 90°.

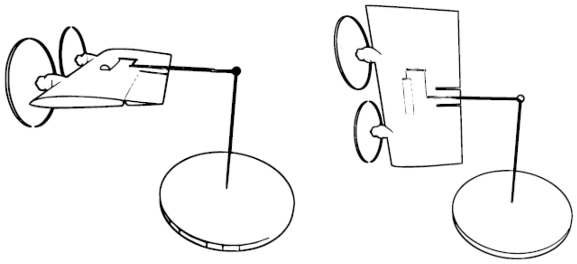

Fig. 11 – Two-degree of freedom sting-mounted experimental setup.

An adapted *MAVion* wind tunnel model has been fabricated for the wind tunnel campaign (Fig. 12). The model was equipped with motors and elevators wirelessly controlled from the ground control station.

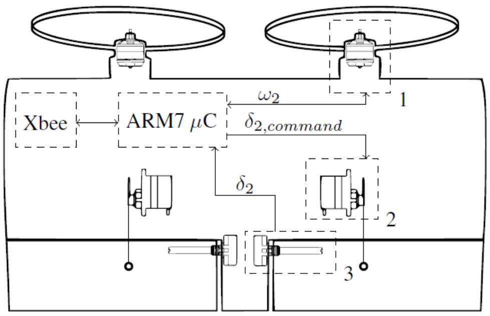

Fig. 12 – The *MAVion* wind tunnel powered model.

Only electrical power was supplied to the vehicle from outside the wind tunnel test section. The wind tunnel ground station communicates with the wind tunnel model onboard ARM7 micro-controller by means of an *XBee* wireless connection in order to minimize the number of wires and the parasite forces and torques due to their intrinsic stiffness. The wind tunnel ground station controls motor speeds and elevators deflections in an open-loop configuration, receiving telemetry data from *MAVion* (motor rpm values, elevator deflection angles) while receiving data from the balance and registering all measured values.

VI. RESULTS AND DISCUSSION

In addition to a full flight model identification, the wind tunnel campaign has provided some interesting results about the equilibrium transition. It should be pointed out that in the present study, only a pure longitudinal equilibrium transition (no sideslip angle) has been investigated. Proceeding to an experimental equilibrium transition test has required adjusting 4 different parameters: wind tunnel speed, model angle of attack, motors rpm, elevators deflection angles. Since the wind tunnel speed needs some time to stabilize to a constant value, it is gradually reduced from its maximum value (25 m/s) down to zero. For each wind speed value, the angle of attack is adjusted so that the lift force equals the required prototype weight. Both motors are then started and rpm values are adjusted so as to cancel the horizontal force. Then, the elevator deflection angle is adjusted so as to obtain a zero pitching moment with respect to the expected prototype center of gravity located 10% chord upstream the aerodynamic center. Because tilting the elevator or changing motors rpm would affect the level of lift force generated by the vehicle, the process is iterated until convergence.

The results are illustrated in Fig. 13 which shows that the *MAVion* can fly from 0 up to nearly 20 m/s. At its maximum speed, the *MAVion* has an angle of attack of 6°. Flying at a lower angle of attack would require drastically increasing thrust which is limited by the motor capability.

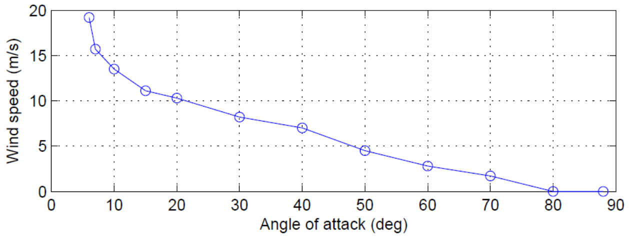

Fig. 13 – Wind speed in equilibrium transition from 0 to 90° angle of attack.

Although Fig. 14 does not show the actual mechanical power acting on the motor shaft, one can observe that the motor speed is minimum when the angle of attack reaches 15° which corresponds, from Fig. 13, to a wind speed of 11 m/s. That point of minimum motor speed might be close to the minimum power flight point that defines the cruise condition at which endurance is maximized.

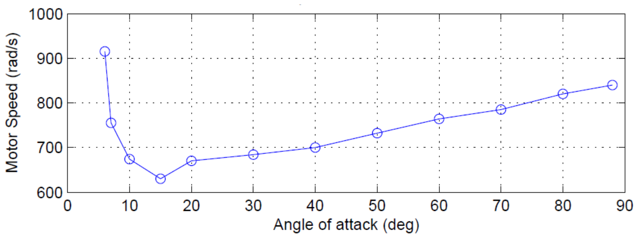

Fig. 14 – Motor speed during equilibrium transition from 0 to 90° angle of attack.

Fig. 15 displays the flap deflection angle necessary to obtain the pitching moment equilibrium during transition. A maximum value of 27° is required to balance the vehicle nose-up moment when the vehicle is at 40° angle of attack, that is around 7 m/s. As a consequence, elevators remain efficient throughout the entire transition.

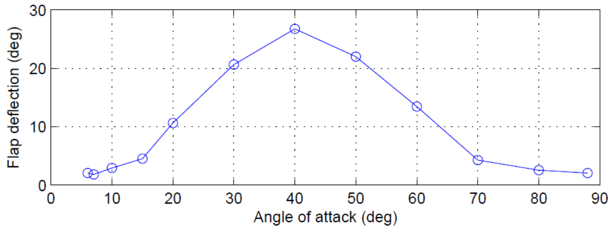

Fig. 15 – Flap deflection angle during equilibrium transition from 0 to 90° angle of attack.

An outdoor version of the *MAVion* has been equipped with winglets which act as vertical tails and provide passive stability in roll. The triangular shape of the winglets has been designed in order to keep the elevators tips in contact with the winglets even when fully tilted (up to 30°). By doing so, the elevators tips always remain limited by the winglets, which eventually reduces tip losses.

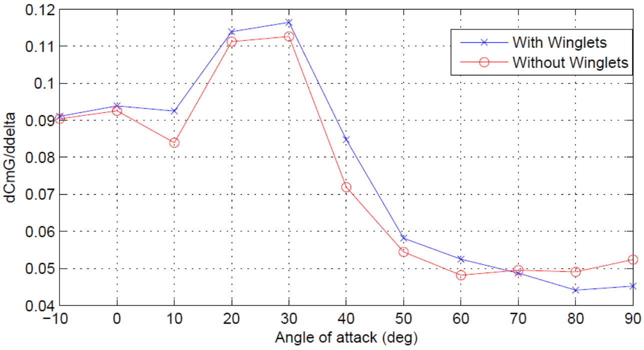

Fig. 16 – Flap efficiency during equilibrium transition from 0 to 90° angle of attack.

As illustrated by Fig. 16 which shows the pitching moment gradient with respect to the elevator deflection angle for varying values of the angle of attack, the elevator efficiency is increased when winglets are added. Interestingly, winglets significantly enhance the elevators efficiency particularly in the middle of transition (around 40° angle of attack) when the elevators are tilted at their maximum value (see Fig. 15). At that specific transition point, the pitching moment gradient equals to 0.07 without winglets while it reaches 0.085 with winglets, which represents an increase of more than 20% in aerodynamic efficiency.

Also, it is noticed that the additional skin friction drag due to the additional winglets wetted area is not visible on the aerodynamic polar (Fig. 17) while the induced drag is significantly decreased at high lift forces. It should be mentioned that negative aerodynamic coefficients are due to the thrust component since motors are active.

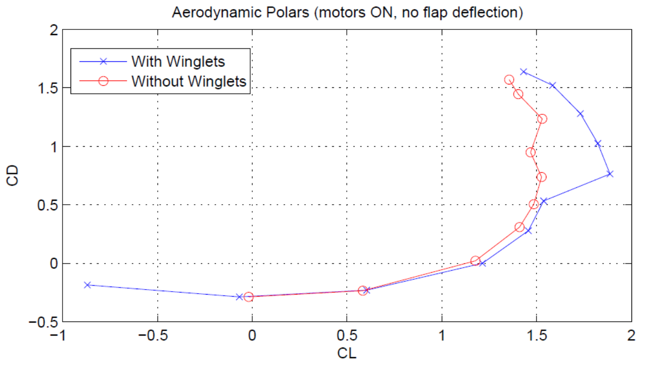

Fig. 17 – Effect of winglets addition on the aerodynamic polar.

On a practical viewpoint, adding winglets may be useful to protect the elevators and to provide a natural landing device.

VII. CONCLUSIONS

Combining the capability of achieving horizontal and vertical flight with the same micro aerial vehicle opens the way to almost unlimited recognition missions both in outdoor and indoor environments. The tilt-body concept, also known as “tail-sitter” because of its VTOL capabilities, consists of associating rotors and fixed wings within the same vehicle in such a way that it can be operated in airplane mode, in helicopter mode and in transition flight without resorting to embedded moving mechanisms such as in the tilt-rotor or in the tilt-wing configurations. Multi-tasking recognition missions may be performed in highly confined or complex environments such as forests, tunnels or caves by adding free wheels.

A tilt-body MAV configuration has been investigated. A simple flying wing powered with two counter-rotating propellers in tractor configuration has been proposed and tested in a low-speed wind tunnel. The wind tunnel campaign has provided a large database for angles of attack and sideslip angles ranging from 0 to 90°. The database will be used to develop a flight dynamics model and to determine control laws. Preliminary analysis of the equilibrium transition study indicates that full equilibrium is achieved during transition both in forces and moments. Adding winglets not only provide lateral stability in airplane mode but they also improve the aerodynamic efficiency while the extra skin friction drag is compensated by the lower induced drag.

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