

## **On the Effect of Winglets on the Performance of Micro-Aerial-Vehicles**

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# On the Effect of Winglets on the Performance of Micro-Aerial-Vehicles

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## Abstract

*In recent years an increased interest in developing Micro-Aerial-Vehicles (MAVs) has been expressed by various military and civilian entities. The current study computationally investigates how winglets can be used to potentially improve the aerodynamic performance of this tiny vehicle. Preliminary results and ongoing work will be presented along with the description of the requirements imposed on the design of MAVs.*

## 1. Introduction

Mankind has always had the desire to build bigger, better, or faster machines. In the aerospace industry, ever since the Wright brothers' first flight on December 17<sup>th</sup> 1903 the goal has been to fly faster, cover longer distances, and reach higher altitudes [1]. But recently this has changed dramatically.

Since the mid-1990's an increased interest in developing Micro-Aerial Vehicles (MAV) has been expressed by both civilian and military organizations [2]. This has caused many popular science magazines to devote space for the subject, thus making more people aware of it [3-4]. During the recent military excursions in Afghanistan and Iraq, a small, unmanned aircraft called "DragonEye" was used to submit a picture of the road ahead to the troops revealing dangers and thus saving lives. The pictures captured by the DragonEye have been shown on TV, giving the general population a better picture of the battlefield and practically bringing the war into our living rooms.

The idea of a small flying vehicle that could be used, for example, for surveillance was first introduced by Hundley and Gritton in 1992 who thought that it would take just 10 years for one to develop a 1 cm wingspan vehicle that would be able to carry a 1 gram payload [5]. This goal has not been achieved and one

can honestly state that their goal was not a realistic one. There is however a logical explanation for their idea as at that time no studies had been done on such small-scale aerial vehicles. The smallest airplanes in use at that time were the Unmanned Aerial Vehicles (UAV) that had a wingspan on the order of meters. Technology advances with time and in terms of the equipment that goes onboard an MAV it would be almost possible to get the size down to a mere centimeter. However, due to insufficient knowledge of small-scale aerodynamics they failed to realize that an MAV is not just a scaled-down airplane, but a completely new design that has to take into account the size restrictions from the very beginning [6].

Currently an MAV is defined as having a nominal maximum dimension of 150 mm in any direction as required in the MAV research program supported by the Defense Advanced Research Projects Agency (DARPA) since 1995 [6]. The current goal of the DARPA program is to develop a vehicle that weighs less than 90 g and is able to carry a payload of 18 grams. Eventually the MAVs are required to be capable of reaching speeds up to 20 m/s and flying 20 to 30 minutes while submitting continuous video feed filmed by an onboard camera [7]. These definitions place an MAV into the group of birds based on its size and flight speed. This has motivated many researchers to study natural flight as a possible solution to the MAV-design problem [8-9].

The size limitation is caused by the requirement that an MAV should be invisible to radar as well as operable by a single user who should be able to carry both the vehicle and the equipment required to control it in a backpack. The cost of the vehicle should be less than \$1,000 and it should not carry any classified equipment onboard thus making it discardable in case of a crash [10]. The aforementioned DragonEye does not even come close to satisfying these goals, having a wingspan of 114 cm, a maximum chord of 91 cm and weighing about 20 times more than an MAV [11-12]. It

should be noted also that a typical mission of the Dragon Eye consists of cruising at about 10 m/s at altitudes of 90 to 150 m, which is very similar to the requirements for the MAV program. But it fails to satisfy the price goal: The Dragon Eye system consisting of the ground control equipment and two air vehicles comes with a hefty price of \$70,000. Even with its high cost, it is well worth its value if it helps to save human lives. The Marines currently have 40 of these systems in use [12].

The proposed uses of MAVs that are of interest to the DARPA program are military missions such as reconnaissance, placement of unattended sensors, surveillance, detection, communications, and ammunitions deployment [2]. An MAV is intended for use at the platoon level, which would lead to minimal data transmission time and thus enable a quick response by the troops. This would be a clear benefit compared to UAVs, which due to their size are often controlled from a location far away from the individual soldiers. Thus by the time the information gathered by UAVs reaches the platoon level the target may already have moved [4,10]. It has also been proposed that an MAV could be used for urban surveillance or by fire departments to look for people inside a structurally unsafe building after a fire or an earthquake [6].

## 2. Aerodynamic considerations

The description of an MAV and its proposed mission bring along two important physical phenomena that have to be taken into account when designing an MAV. The first one is the low aspect ratio (wingspan-to-chord-ratio) that leads to deteriorated performance and the second one the low speed combined with the size that leads to a low-Reynolds number flow for which the dominant viscous effects decrease the overall performance [7].

The flow can be considered incompressible for Mach number less than 0.3. The Mach number is the ratio of the speed of the flow to the speed of sound. Incompressibility implies that the density of the fluid is considered to remain constant. As MAVs operate in standard air at low altitudes, the speed of sound is approximately 340 m/s. The maximum speed for an MAV is 65 km/h or about 18 m/s so the Mach number is approximately 0.05.

The Reynolds number is the lone dimensionless parameter in the governing equations of the motion of an incompressible fluid and is defined as

$$\text{Re} = \frac{UL}{\nu} \quad (1)$$

where  $U$  is the freestream velocity far away from any bodies in the flow,  $L$  is the characteristic length of the problem and is usually chosen to be the chord length of the wing, and  $\nu$  is the kinematic viscosity of the fluid.

The MAVs are said to operate at low Reynolds number as both the  $U$  and  $L$  are much smaller than for larger and faster aircraft thus leading to a much lower  $\text{Re}$ .

At the tips of any wing the high pressure flow on the bottom surface of the wing and the low pressure on the top surface of the wing must be equal. Clearly, these are generally not equal along the wingspan as this would lead to a non-lifting wing. The existing pressure difference causes the flow from the bottom side to curl to the top creating a tip-vortex and downwash at the wing tip. This downwash lowers the effective lift obtained with the wing and leads to an increase in drag. This additional component of drag is called the "induced drag" or "drag-due-to-lift" as it is absent in case of a non-lifting wing. The drag increase is due to the tip-vortex that causes an energy loss in the flow.

The magnitude of the induced drag can be estimated by using the definitions of the dimensionless force-coefficients and the aspect ratio of the wing [13]:

$$C_{d,i} = (1 + \delta) \frac{C_L^2}{\pi AR} \quad (2)$$

The above shows that the induced drag coefficient depends on the lift-coefficient, the aspect ratio and the geometry of the wing, which affects the value of  $\delta > 0$ . The optimum value of  $\delta = 0$  is only of theoretical interest as it is only obtained in case of an elliptic wing with an elliptic lift-distribution in an inviscid flow [13]. In terms of the actual forces (2) becomes:

$$D_i = (1 + \delta) \frac{\text{lift}^2}{\frac{1}{2} \rho U^2 * \pi b^2} \quad (3)$$

where  $b$  is the wing-span. Thus, the induced drag depends only on the lift and the span of the wing and increases rapidly as the wingspan decreases. This suggests that an increase in wingspan would lead to a decrease in induced drag. However, this cannot be done due to the size limitations imposed on the MAVs [6] and one has to seek alternative means for induced drag reduction, i.e. ways of reducing the value of  $\delta$ .

## 3. Winglets

The addition of winglets, i.e. vertical or close-to-vertical wings to the tips of a wing has gained major attention since Whitcomb's work in 1976 [14]. The idea of winglets was however presented much earlier and studies on the effect of winglets or endplates were performed by Hemke in 1920's [15].

The motivation for the use of winglets is to prevent or restrict the imminent downwash at the wing tips. Studies conducted previously on the effect of the winglets on the performance of transonic transport vehicles and sailplanes have shown that the winglets can improve the performance of an aircraft through induced drag reduction. At some cases an overall drag reduction

has also been observed although the addition of winglets does increase the surface area of the vehicle thus leading to higher frictional drag. It has also been observed that increasing the wingspan does lead to similar reduction in induced drag as the addition of a winglet does [14].

Figures 1 and 2 show the flow-visualization of the tip-vortex over an MAV with and without winglets [16]. It can be seen that the addition of a winglet moves the tip-vortex up and away from the main wing, thus causing less downwash at the wing and resulting in an increase in the lift obtained with the wing.



**Figure 1. Flow-visualization of the tip-vortex for the MAV without a winglet.**



**Figure 2. Flow-visualization of the tip-vortex for the MAV with a winglet.**

#### 4. Computational approach

The current computations have been performed using Cobalt, which is a commercially available cell-centered, point-implicit Finite Volume solver that solves the unsteady, compressible Navier-Stokes Equations. It has been developed from the government owned code Cobalt<sub>60</sub> that was developed at AFRL Wright-Patterson by Strang et al. during the later half of 1990's [17]. It is generally accepted that a compressible flow solver can be used to solve for incompressible flow problems. In the current study, all computations have been completed

for Mach number 0.1 following previous researchers who have used compressible flow solvers for incompressible flow problems [17-18].

The fundamental method behind Cobalt is the approximate Riemann solver of Gottlieb and Groth that solves the unsteady, inviscid Euler equations. The viscous fluxes have been added to that algorithm. The original, explicit temporal integration has been replaced by an implicit approach and the code has been parallelized using the Message Passing Interface (MPI). The parallelization utilizes the ParMetis software subdivides the full computational grid into nearly equally sized zones, which are assigned to each available processor [17].

The computational grids have been created using Gridgen by Pointwise®, Inc [19]. Gridgen is a block-based grid generation software which can create structured, unstructured, and mixed meshes. The mixed meshes have been shown to be the most effective approach in modeling viscous 3-D flows due to their superior capability in both capturing the strong gradients in the near-wall boundary layers using structured cells and in modeling complex geometries using unstructured cells [20]. For this reason the mixed meshes have been used exclusively in the current study. The two-dimensional computations have been performed using either structured or mixed meshes.

#### 5. Current results

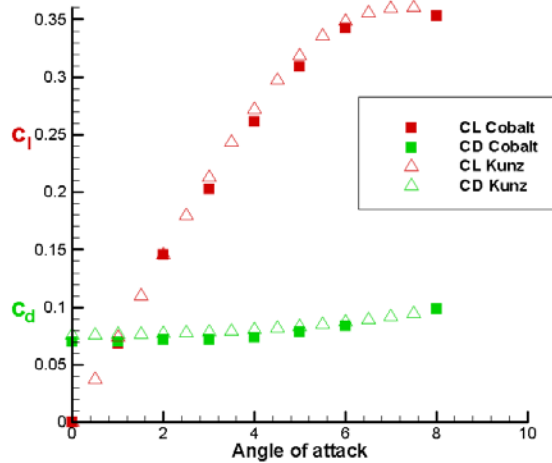
In order to provide reliable computational results, any computational approach has to be validated and verified. Validation is understood as comparison with real life, such as experimental results. Verification on the other hand consists of comparison with analytical solutions and previous reliable computational results. In fluid dynamics the analytical solutions are nearly impossible to find and thus comparison with other numerical results is generally used for verification [21].

Cobalt<sub>60</sub> has been validated and verified for a variety of problems [17]. The validation and verification in the current study investigates the effect of the computational grid in the results as well as the effect of the user-defined parameters within the code. The additional validation is necessary as Cobalt has not been widely used for low-Reynolds number studies.

Figure 3 shows the lift and drag coefficients for a NACA0008 airfoil at  $Re = 2,000$  obtained in the current study along with earlier computational results [22]. The two data sets are in excellent agreement. This case was chosen for verification as the flow is fully laminar and for angles-of-attack away from zero degrees does lead to separation. Various computational grids were used in the current study to ensure that the reported results are converged.

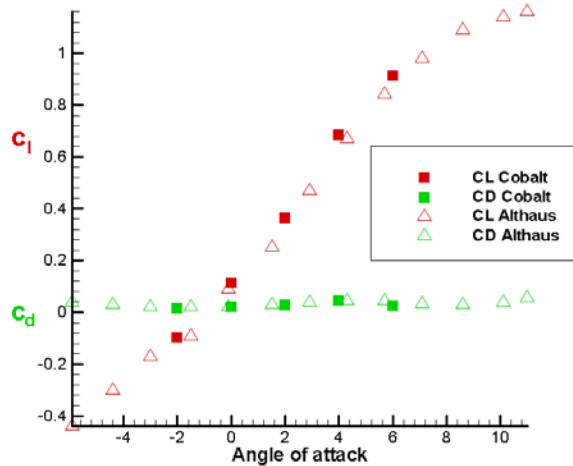
In Figure 4, a comparison with experimental results is shown for an Eppler-211 airfoil at  $Re =$

60,000. This case is slightly more interesting, as this Re is within the Re-range at which MAVs operate. The data shown is in good agreement with the experimental results [23].



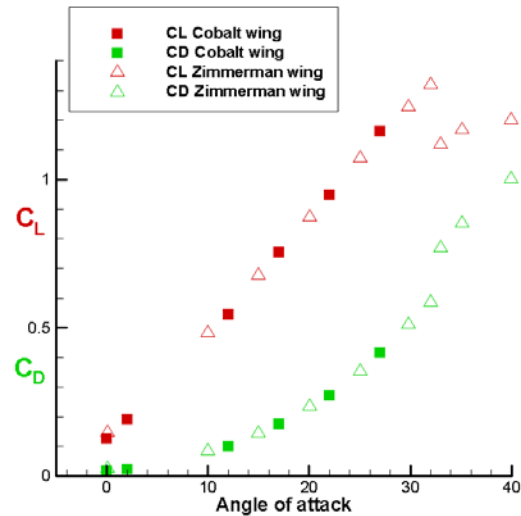
**Figure 3. The lift and drag coefficients for a NACA0008 airfoil at Re = 2,000.**

It should be emphasized that comparison with any experimental results is very difficult at the low-Reynolds number range due to inherent 3-D phenomena in experiments, the turbulence level in the wind tunnel, the sensitivity of the equipment used, and other factors that cause the test results from different facilities to differ sometimes by even 40 % [24]. Remembering that the computational world can be made fully 2-D and turbulence free, the two data sets in Figure 4 may be as close as one can get without using turbulence modeling.



**Figure 4. The lift and drag coefficients for an Eppler-211 airfoil at Re=60,000.**

The approach used to compute 3-D problems has an additional difficulty: one has to create a grid that is able to capture the tip-vortex in addition to the boundary layers and the wake that are present in 2-D as well. The 3-D approach has been validated for a rectangular aspect ratio 1 wing that has the shape of a Clark-Y airfoil. The comparison with experiments at chord Reynolds number 860,000 [25] is shown in Figure 5 and shows an excellent agreement.



**Figure 5. The lift and drag coefficients for the Clark-Y wing with AR=1.0 at Re = 860,000.**

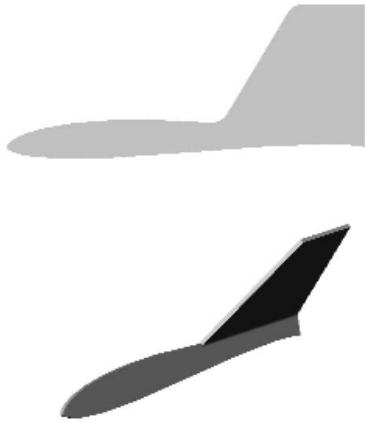
The actual MAV-geometry of interest in the current study is shown in Figure 6. The basic airfoil used for the design is an Eppler-212. The maximum chord length is 150 mm and the tip chord length 127 mm. The full span of the vehicle is 150 mm. It has a swept leading edge and a straight trailing edge [16].



**Figure 6. The baseline MAV-design.**

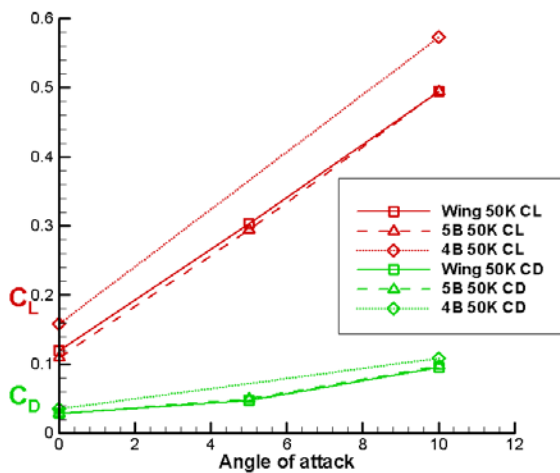
The winglets investigated in the current study are flat plate winglets that are attached at the tips of the

baseline model. The winglets are not designed specially for the computational study but are the same ones previously investigated experimentally [16]. Figure 7 shows two examples of the winglets.



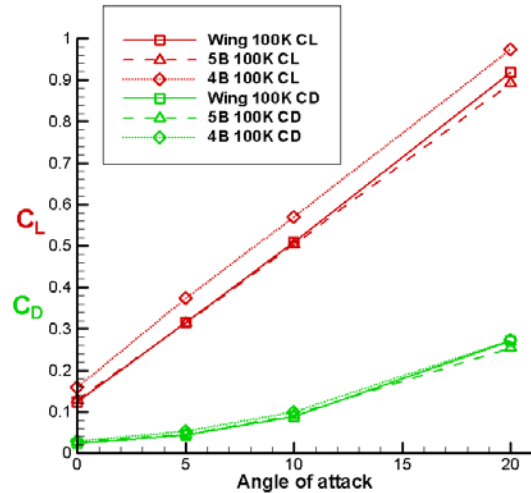
**Figure 7. Two winglet designs [16].**

The parameters varied in the experimental study were the leading-edge sweep angle of the winglet, the height and the tip chord of the winglet, the cant angle, and the location of the winglet along the span [16]. Two winglets were chosen based on the experimental results for the current computations based on the overall performance for the Re-range 60,000-150,000. Both of these have a 26.6° leading edge sweep and a 25.4 mm span. The winglet 4b, which based on the experiments [16] appears to be the best design has a 78 mm tip chord and the winglet 5b has an 8 mm tip chord.



**Figure 8. Lift and drag coefficients for the baseline wing and two winglet models at Re=50,000.**

The effect of adding these winglets at the tips of the baseline wing design are shown in Figures 8 and 9 for Re = 50,000 and Re = 100,000, respectively.



**Figure 9. Lift and drag coefficients for the basic wing and two winglet models at Re = 100,000.**

As can be seen, the winglet 5b does not improve either lift or drag characteristics of the MAV and thus should not be used for the design. The larger 4b-winglet however shows a significant increase in lift at both Reynolds numbers. This increase is accompanied by an increase in drag, which is caused by the pressure force and the skin friction force acting on the additional surface area. However, the amount of induced drag is reduced despite the increase in  $C_L$ . Recalling Equation (3), the value of  $\delta$  must have decreased significantly.

The increase in lift is sufficiently large to offset the negative effects of the drag increase. The thrust needed to overcome the higher drag is obtainable from small engines [26], the additional lift achieved with the winglets attached to the model will help the MAV to carry the payload as required [6-7]. The increase in lift through the addition of 4b-winglets is also increases the overall lift-to-drag-ratio, which is generally used as the measure of aerodynamic efficiency [7].

## 6. Ongoing work

The computations are currently being performed for other Reynolds numbers within the MAV-operating range of Re = 50,000 – 150,000 for both of the above mentioned winglets. The effect of a canted, non-vertical winglet will also be studied. The overall benefits of winglets will be determined based on the effect on the performance of the vehicle at various Reynolds numbers and angles-of-attack. The most important factor is the potential increase in lift followed by an increased lift-to-drag-ratio. The moments acting

on the vehicle will be calculated and the effect of the winglets on the stability of the MAV addressed.

## 7. Conclusions

The computational approach used in calculating flow fields around MAVs has been presented, validated, and verified. Computations investigating the effect of the winglets on the performance of an MAV are currently underway. The reported results suggest that the addition of winglets to an MAV can improve the lift characteristics and the lift-to-drag ratio of the vehicle significantly. However, one must be careful when choosing a winglet as ill-designed winglet can also reduce the performance of the MAV.

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