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Micro-article

# Aerodynamic optimization of a VTOL drone using winglets

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ABSTRACT

In this work, an aerodynamic optimization of a VTOL drone wing has been carried out by implementing winglets. A dual methodology has been used employing a CFD study with the open source code OpenFOAM and applying the Vortex Lattice Method with the open source tool XFLR5 for different configurations and wingtips: the original wing, raked wingtips, and blended winglets. A comparison between the two software has been conducted to determine the validity of XFLR5 and to quantify the error in calculating the aerodynamic coefficients and the bending moment. XFLR5 offers the same trends as RANS at a fraction of the cost, allowing the use of XFLR5 for the first stages of design.

Drones applications are becoming wider, representing a technology of great interest and in continuous development. For example, they have become an unexpectedly formidable weapon in the Ukraine war. One of the drones' main limitations is their range and autonomy. These parameters depend on the batteries and the aerodynamic efficiency [1]. In recent years, different techniques have been studied to increase the efficiency of drones [2]. Among them, the use of winglets stands out [3].

In this study, an aerodynamic optimization of a VTOL (Vertical Take Off and Landing) drone has been performed by implementing winglets and wingtips. We have compared two methodologies to perform this type of study, the Vortex Lattice Method (VLM) and a Computational Fluid Dynamics (CFD) model. The first is a non-viscous model that could lead to errors or lack of precision in the results [2,4,5]. CFD methods have been used accurately in aerospace applications [6–10] but with the penalty of much higher computational cost. Therefore, we study the accuracy and feasibility of the two numerical models, presenting an algorithm that allows for faster wing optimization.

The reference wing was selected based on the actual one (NACA 4412 airfoil) of a VTOL drone [11]. This wing has a rectangular platform shape and an aspect ratio of 8. The chord is 150 mm, and the half-wingspan is 600 mm.

The VLM was performed in XFLR5 due to its high reliability in modeling complex surfaces such as winglets [4]. The airfoil mesh has 300 panels, while the wing has 10148 panels. A Type 1 study, i.e., changing the angle of attack (AOA) while keeping fixed the free stream (18 m/s) and the Reynolds number ($Re = 183000$), was run [11].

Two devices were studied: blended winglets and raked wingtips, as shown in Fig. 1. A parametric study of 9 raked wingtips configurations was performed, setting the sweep angle (SA) to 30°, 45°, and 55° and the taper ratio (TR) to 0.25, 0.35, and 0.4. This study was carried out keeping the wetted area of the models constant, allowing for a comparative analysis of the non-dimensional coefficients. Then, a parametric study of 27 blended winglet configurations was performed analyzing three cant angles (CA): 45°, 60°, and 70°; 3 winglet heights (WH): 60, 90, and 120 mm (10%, 15%, and 20% of the wing semispan) and 3 TR: 0.2, 0.3 and 0.4. In this case, the mere comparison of non-dimensional coefficients was not representative since the wetted area of the different blended winglets was not constant. For this reason, a comparative analysis of the dimensional forces was performed.

Regarding raked wingtips, Table 1, the induced drag was improved for every configuration. The optimum corresponds to $SA = 30°$ and $TR = 0.25$ as in [12,13]. However, this configuration causes a high bending that would need reinforcement, affecting the aerodynamic performance. A limitation of a 5% increase was imposed in this parameter, resulting in $SA = 45°$ and $TR = 0.4$, for a reduction of 5% in the total drag.

In the case of the blended winglets, the most significant total drag reduction was achieved with the intermediate taper ratio, as shown in Fig. 2, because the lift distribution was the closest to the ideal elliptical distribution [14]. For every case, the increase in the bending moment was below 5%. The optimum is obtained for $CA = 70°$, $WH = 120$ mm, and $TR = 0.3$. This configuration reduces the induced drag a 13.1% and the total drag by 4.8%. On the other hand, the efficiency and momentum increased a 5.1%, and 2.4%, respectively.

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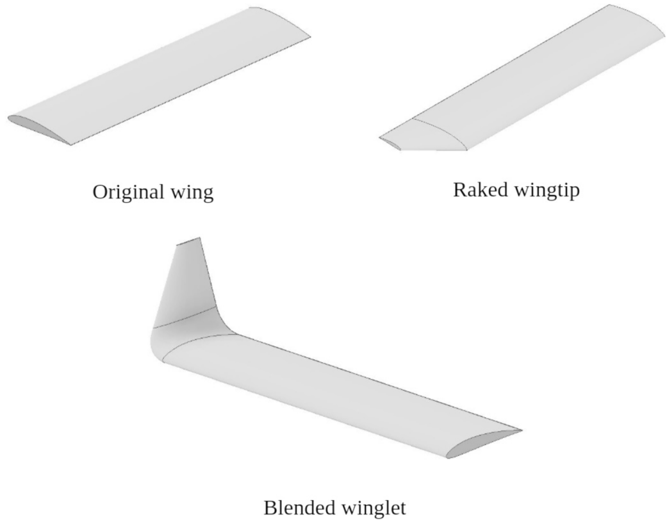


**Fig. 1.** Geometries studied.

**Table 1**
Induced drag for raked wings as a function of AOA for different configurations.

| | | $\alpha = 2°$ | $\alpha = 3°$ | $\alpha = 4°$ |
|---|---|---|---|---|
| Original wing | | 0.0102 | 0.0137 | 0.0177 |
| TR= 0.25 | SA= 30° | 0.0092 | 0.0124 | 0.0161 |
| | SA= 45° | 0.0097 | 0.0131 | 0.0170 |
| | SA= 55° | 0.0099 | 0.0134 | 0.0173 |
| TR= 0.35 | SA= 30° | 0.0095 | 0.0129 | 0.0167 |
| | SA= 45° | 0.0099 | 0.0133 | 0.0173 |
| | SA= 55° | 0.0100 | 0.0135 | 0.0175 |
| TR= 0.45 | SA= 30° | 0.0972 | 0.0130 | 0.0167 |
| | SA= 45° | 0.1000 | 0.0134 | 0.0174 |
| | SA= 55° | 0.0101 | 0.0136 | 0.0175 |

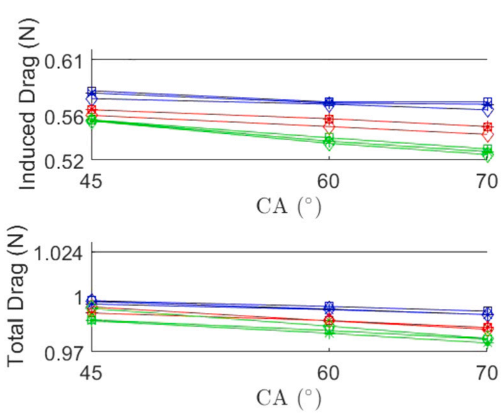


**Fig. 2.** Blended winglets: induced (top) and total (bottom) drag as a function of the CA. Blue, red, and green lines correspond to $h = 60, 90, 120$ mm, respectively. Squares, stars, and diamonds represent TR= 0.2, 0.3, 0.4.

The CFD study was carried out with the open-source tool OpenFOAM. Three geometries were analyzed: the original wing and the optimum geometries. These geometries were designed in Inventor. The mesh was generated with the ANSYS Meshing tool. A mesh independence study and wake and vortex region refinement were carried out. In both studies, the mesh was selected in such a way that, while complying with a grid convergence index (GCI) of less than 1% (Table 2 and Table 3), it achieved a balance between refinement quality and associated computational cost. The resulting mesh consisted of an unstructured tetrahedral mesh of 25.7 million elements. As an example,

**Table 2**
Mesh independence study for AOA = 3°.

| | Nº elements | GCI $C_L$ | GCI $C_D$ |
|---|---|---|---|
| **M1** | 7917189 | – | – |
| **M2** | 12311460 | 0.46% | 0.73% |
| **M3** | **17458844** | **0.27%** | **0.99%** |
| **M4** | 25148773 | 0.08% | 0.83% |

**Table 3**
Wake and vortex region refinement study for AOA = 3°.

| | Nº elements | GCI $C_L$ | GCI $C_D$ |
|---|---|---|---|
| **M3** | 17458844 | – | – |
| **M3.1** | 17684352 | 0.05% | 0.14% |
| **M3.2** | 24245424 | 0.06% | 0.11% |
| **M3.3** | 24704761 | 0.13% | 0.04% |
| **M3.4** | **25654311** | **0.06%** | **0.20%** |

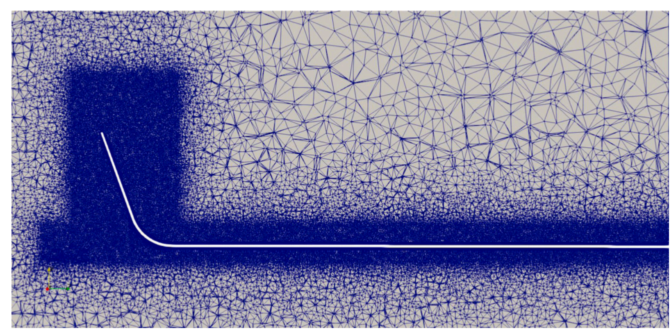

**Fig. 3.** Blended winglet mesh.

Fig. 3 shows the mesh of the blended winglet. The procedure was validated with experimental data in similar wings. The turbulence model chosen was Spalart-Allmaras [15]. Seven angles of attack of 0, 3, 4, 6, 9, 12, and 15 degrees were simulated.

Both optimized configurations generated lower total and induced drag than the original wing, achieving the main purpose of the wingtip devices. However, the highest aerodynamic efficiency was obtained with the raked wingtip configuration. This model offered an overall drag reduction of 6.3% compared to 4.6% for the blended winglet model. Despite being the most efficient wing, as with VLM, it also resulted in a too-high bending moment.

The study's final phase compared the results obtained with OpenFOAM and XFLR5, Fig. 4 and Table 4. The goal was to determine the validity of using XFLR5 for initial design phases due to the lower computational cost. For reduced angles of attack, several trends were observed. First, an overestimation of viscous drag of 4% and an underestimation of total drag was noticed. This is because the VLM is a linear method that implements an inviscid flow assumption. The calculation of 3D viscous drag is based on the interpolation of 2D parasitic drag from the local wing lift. Consequently, the lift obtained is a linear function with the angle of attack. Therefore, total drag is underestimated. On the other hand, XFLR5 was found to overestimate total lift by 1%-5% and underestimate induced drag by 20%. This can be explained because the software models the wake as a straight extension of flat panels, resulting in overestimating the lift and vortex strength [16].

Despite these errors, it should be noted that the trends observed in CFD and XFLR5 results concerning the original wing are maintained. This fact allows the XFLR5 analysis tool to be validated for initial design phases, as correct trending of the results can be obtained with far lower computational cost.

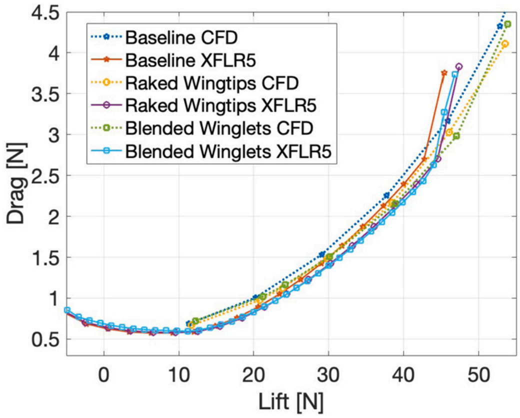


**Fig. 4.** Drag as a lift function for all the cases considered, using both RANS and XFLR5.

**Table 4**
Summary of the quantities of merit for a fixed lift requirement.

| | | L (N) | $D_i$ (N) | D (N) | L/D |
|---|---|---|---|---|---|
| Baseline | VLM | 23 | 0.6115 | 1.02403 | 22.46 |
| | CFD | 23 | 0.74 | 1.1475 | 20.04 |
| Raked w. | VLM | 23 | 0.5555 | 0.9733 | 23.63 |
| | CFD | 23 | 0.67 | 1.075 | 21.40 |
| Blended w. | VLM | 23 | 0.5275 | 0.9748 | 23.59 |
| | CFD | 23 | 0.665 | 1.095 | 21.00 |

Finally, a summary of the behavior of the models studied has been presented by comparing the quantities of merit for a minimum lift requirement (23N) needed to fly in cruise mode, defined based on the wing dimensions and the typical range of angles of attack for VTOL drones.

In conclusion, in this work, an aerodynamic optimization of a VTOL drone has been performed using raked wingtips and blended winglets. By comparing the results obtained with OpenFOAM and XFLR5, it has been found that XFLR5 leads to an overestimation of lift and viscous drag and an underestimation of induced and total drag. However, the trends observed with both software are maintained. Therefore, XFLR5 has been validated as a useful tool in the initial design phases for wingtips in VTOL drones. Hence, this software gives an advantage in terms of computational cost and simulation time.

## Data availability

Data will be made available on request.


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