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Computational analysis and validation in wind tunnel of wing-tip devices for unmanned aerial vehicle (UAV)

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Summary. The application of UAV systems within the civil and military aeronautical market encouraged the development of options that increase the performance of this type of aircraft. This paper´s objective is to analyze the aerodynamic behavior of a wing with and without wingtip devices (winglets) for a UAV, through the CFD software Tdyn and wind tunnel tests validation. The lift (Cl) and drag (Cd) coefficients of the wing without winglets were compared to the wing with different curvature winglets at specific angles of attack for maximum Cl/Cd ratio. The results showed that the wing with a winglet can offer an improvement in the Cl/Cd coefficient of 4.5% compared to the wing without any other type of device on the wingtip.

Keyword. UAV, CFD, Wind tunnel validation

1 Introduction

A body that moves through a fluid generates a resultant force, if the fluid is air, this resultant force is generally decomposed into lift force and drag force. In aeronautics it is of special interest to reduce drag or increase lift, there are several methods to achieve these changes, the method analyzed in this investigation is the use of wingtip devices. Frederick Lanchester proposed in 1897 to place a vertical plate at the wingtip to mitigate the effects of vortices. It was not until the 70s that Richard Whitcomb managed to design a type of winglet achieving a 4% reduction in total drag when tested on a Boeing 747. Several experimental studies like [1] show an improvement in Cl/Cd of 9.82% with a blended winglet, also [2] studies the range parameter for an electric UAV, with the installation of elliptical winglets it managed to increase the range of the UAV by 9.81%. Another objective to analyze in this research is the feasibility of the mathematical models of the Tdyn software in the laminar range as well as for the turbulent range, in the study [3] five turbulence models were compared using NACA 0012 and 2412 profiles, using Cl and Cd as parameters, concluding that the Spalart-Allmaras and k-omega SST turbulence models were capable of correctly predicting the Cl and Cd values at angles of attack of 0 ° to 9°, however for higher angles no model satisfactorily predicted the values of Cl and Cd. The objective of the study is to analyze the percentage difference in the lift and drag coefficient and the glide coefficient and to observe the range and fuel consumption of a proposed wing, through CFD software with its respective validation in the wind tunnel, in the for validation, a maximum error of 30% is expected between the simulation values and those from the wind tunnel, but it is desired that the physical phenomena be similar, such as the angle of stall.

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2 Equations

For this study, the parameters analyzed were the lift and drag coefficients, these coefficients are defined by the following equations:

$$C_l = \frac{L}{\frac{1}{2} * A * \rho * V^2} \tag{1}$$

$$C_d = \frac{D}{\frac{1}{2} * A * \rho * V^2} \tag{2}$$

According to [4] the equation for the range for a UAV powered by propellers is given by the equation:

$$R{=}\frac{\eta}{c}\frac{C_l}{C_d}ln\frac{W_0}{W_1} \tag{3}$$

The objective will be to analyze the increase in the Cl/Cd that would imply an increase in range or improvement of the variable c (specific fuel consumption) keeping the range constant and see the that would have the same percentage improvement as the range.

3 Simulation

Parameters for the wing design were defined, which are: 10 kg of useful weight, NACA 4415 profile with a maximum Cl of 1.58, stall speed of 15 m/s and cruising speed of 27.7 m/s. To be compatible with the dimensions of the wind tunnel dimensions, an experimental model was designed applying a scaling factor of 1.9. As a result, the new parameters of the experimental model were: 10 kg useful weight, NACA 4415 profile with a maximum Cl of 1.58, stall speed of 28.73 m/s and cruising speed of 53.2 m/s. The Reynolds Number (Re) was also calculated for the stall speed is 3.495x105 and for the cruising speed 6.471 x105, laminar range was assumed for Re < 5x105.

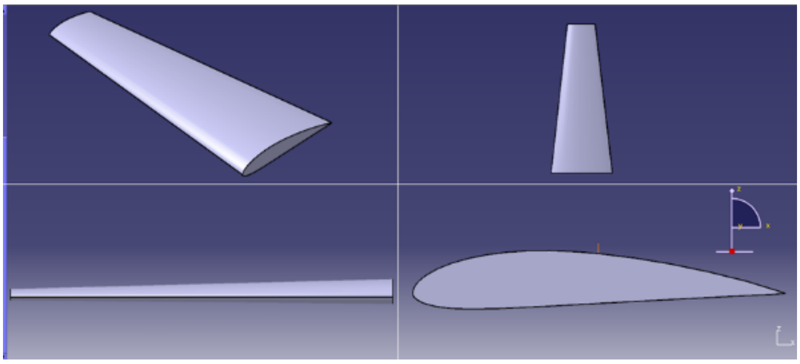

Figure 1: Preliminary wing design in CATIA.

CATIA was used for the design of the wing and the winglets, a couple of aspects were taken into account, the winglets must add a maximum of 3 cm to the wingspan of the wing, the winglet height less than 6 cm, a airfol NACA 0012 with 0° angle of incidence . With these parameters the winglet type 1 was designed.

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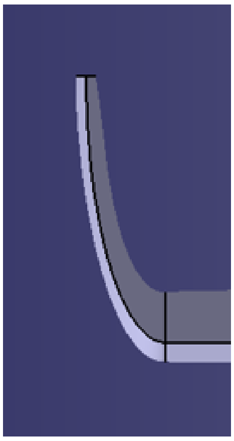

Figure 2: Winglet type 1

By adding 15° and 30° of opening to the wingtles, winglets type 2 and type 3 were obtained.

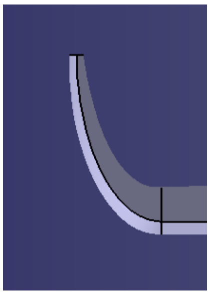

Figure 3: Winglet type 2

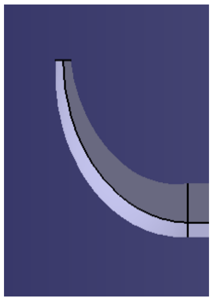

Figure 4: Winglet type 3

For the simulation, the Compass Tdyn CFD+HT Fluid dynamics and multiphysics software was used, and a computer server with 4 AMD Opteron processors with 16 cores each. Tdyn is a numerical simulation solver for multiple physics problems using the stabilized finite element (FIC) method. The following figure shows the algorithm used for the simulations in both flow regimes.

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Flow Solver model	Incompressible
Time Integration	Backward Euler: Implicit 1st order scheme
Solver NonSymmetric	BiConjugateGradient
Tolerance	1.0e-7
Solver Symmetric	Conjugate Gradient
Tolerance	1.0e-7
Preconditioner	ILU
Velocity Advect Stabilization	Auto (4th order and 2nd order)
Velocity norm	1.0e-4
Velocity Boundary type	BasicVBC
Pressure Stabilization	4th order
Pressure norm	1.0e-5
Pressure Boundary type	BasicPBC
Fluid	Air 25°
Modelos de tubulencia	Laminar y K Omega SST
Wall type	no slip condition and y+
Turbulence kinetic energy	0.0382082 m^2s^{-2}
Turbulence length	0.001798 m

Figure 5: Conditions set to the model

A mixed type mesh (structured and non-structured) with tetrahedrons and triangles was implemented on the wing surface and the control volume. After a mesh independence analysis, a mesh was obtained with a total of 5513143 elements and of 937678 nodes, that presented better stability. For the regions close to the wing wall, the boundary layer function was used, specifying its estimated thickness in both ranges.

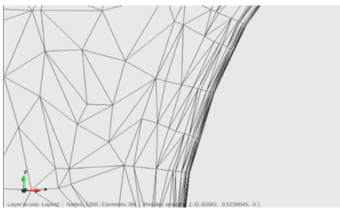

Figure 6: Boundary layer mesh refinement

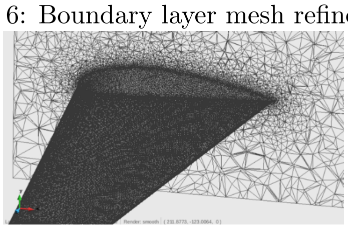

Figure 7: Isometric view of the mesh

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A good convergence and stability was obtained in the solution, adjusting the time increment (dt) in 2.3508e-5 a total of number of step was fixed in 4500 steps. The stability was analyzed using the residual plots of the velocity and pressure fields. For the velocity field the Figure 8 shows residuals up to 1.0e-5 and for the pressure field up to 1.0e-6.

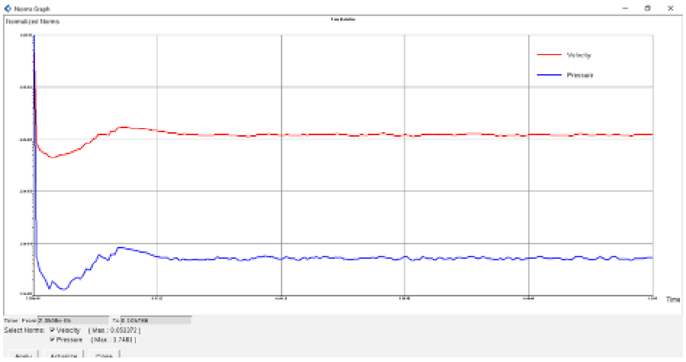

Figure 8: Residual plots of pressure and velocity

3.1 Experimental measurements

For the construction of the wing, a block of cedar-type wood was used and through a CNC machining process, the wing shape was obtained, the winglet was 3D printing.

Figure 9: Wing machinig process

Figure 10: Winglets in the wind tunnel

The following tables show the Cl and Cd results of the simulation and wind tunnel with their respective errors.

AOA	Cl simulation	Cl wind tunnel	Relative error
0°	0,266	0,350	31,55%
2.5°	0,470	0,486	3,49%
5°	0,673	0,617	8,36%
7.5°	0,880	0,778	11,60%
10°	1,113	0,874	21,47%
12.5°	1,332	1,046	21,51%
15°	1,580	1,289	18,45%
17.5°	1,433	0,656	54,25%

Figure 11: Cl simulation and wind tunnel results for laminar range

AOA	Cd simulation	Cd wind tunnel	Relative error
0°	0,032	0,026	21,83%
2.5°	0,042	0,034	26,35%
5°	0,049	0,047	4,10%
7.5°	0,055	0,065	15,30%
10°	0,074	0,089	16,59%
12.5°	0,100	0,134	24,97%
15°	0,130	0,197	34,12%
17.5°	0,223	0,268	16,71%

Figure 12: Cd simulation and wind tunnel results for laminar range

AOA	Cl simulation	Cl wind tunnel	Relative error
0°	0,208	0,282	35,15%
2.5°	0,388	0,480	23,54%
5°	0,578	0,700	21,14%
7.5°	0,778	0,857	10,26%
10°	0,949	0,931	1,95%
12.5°	1,147	1,054	8,07%
15°	1,428	1,191	16,59%
17.5°	1,642	1,306	20,44%
20°	1,530	0,942	38,44%

Figure 13: Cl simulation and wind tunnel results for turbulent range

AOA	Cd simulation	Cd wind tunnel	Relative error
0	0,047	0,041	11,82%
2,5	0,055	0,049	11,13%
5	0,069	0,057	18,44%
7,5	0,091	0,068	25,22%
10	0,118	0,089	24,49%
12,5	0,147	0,107	27,51%
15	0,205	0,148	27,76%
17,5	0,263	0,183	30,66%
20	0,334	0,348	4,13%

Figure 14: Cd simulation and wind tunnel results for turbulent range

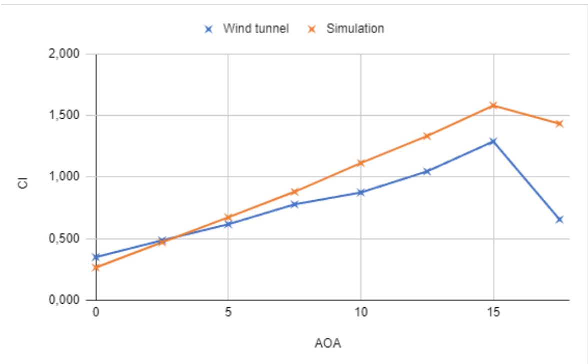

Figure 15: Cl vs AOA laminar range

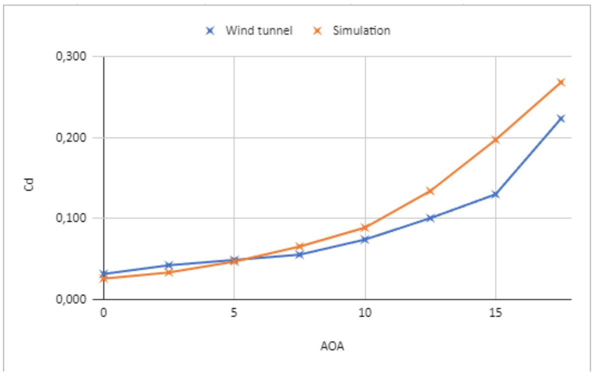

Figure 16: Cd vs AOA laminar range

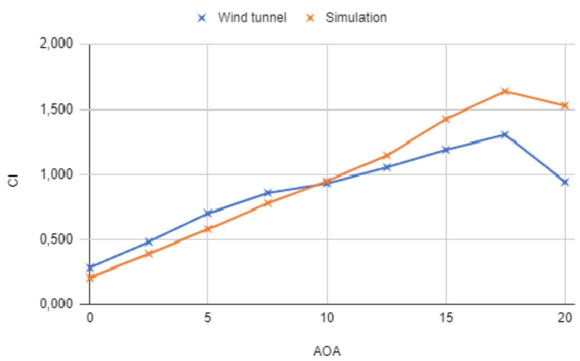

Figure 17: Cl vs AOA turbulent range

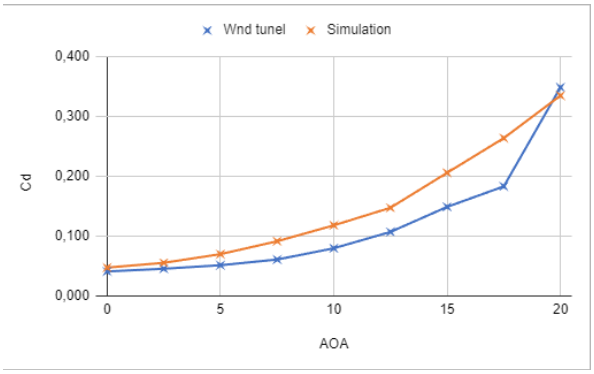

Figure 18: Cd vs AOA turbulent range

The errors between the values of the wind tunnel and the simulations used can be seen in the following tables:

Models	Cl	Cd
Laminar	21,33%	19,99%
K_Omega_SST	19,51%	19,51%

Figure 19: Average measurement errors.

The wind tunnel´s error is between 20% and 30% so it can be seen from the Figure 19 that the simulations gave reliable results.

The next step was to know at which angle the value of Cl/Cd is maximum in order to observe the ranges improvement at the velocity of 53.2 m/s, to archive this Cl/Cd Vs AOA plot was used, Figura 20.

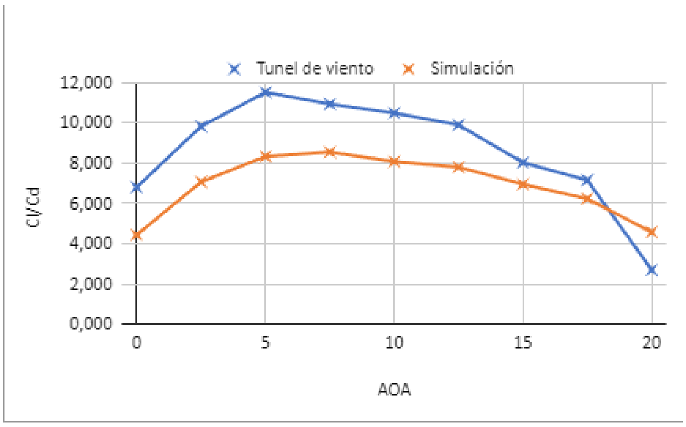

Figure 20: Cl/Cd vs AOA 53,2 m/s.

It can be seen from the figure above that for the angle of 6.9° the Cl/Cd value is maximum. The values obtained from the winglets at the mentioned angle are shown in the following table.

Half wing	Lift	Drag	Cl	Cd	Cl/Cd	Improvement
Wing without winglet	76,540	8,946	2,497	0,265	8,556	—
Wing with winglet type 3	82,482	9,202	2,691	0,272	8,963	4,54%
Wing with winglet type 2	81,765	9,192	2,667	0,272	8,895	3,82%
Wing with winglet type 1	80,910	9,174	2,640	0,272	8,820	2,99%

4 Conclusion

Regarding the simulation environment configuration in Tdyn, the simulations yielded acceptable results after several iterations. Strong relationships were found between the value of dt and the systems stability, obtaining good results with a value of dt that delivered convergence, stability and consistency, something recommended by Tdyn. Also the analysis of the pressure and velocity residual plots were used as a parameter to measure the level of stability in the simulation solution.

Regarding the meshing, the Boundary Layer function of the software proved to be quite useful, managing to capture acceptably the pressure and velocity changes in the boundary layer region. In the other regions of the wing geometry, the meshing turned out to be very sensitive to changes for its refinement, therefore, it was decided to refine the regions of the control volume close to the wing with good convergence levels and acceptable computation times.

It is worth mentioning certain particularities in the models that were used in the established velocity ranges, for the laminar range the Tdyn laminar model was used, which for angles greater than 7.5° the number of convergent iterations was decreasing; but from 17.5° onwards no convergent iterations were found. This phenomenon is assumed because certain models present convergence problems as the boundary layer separates (post-separation zones), the K Omega SST turbulence model used for the turbulent range offered a better performance with very good convergence in post-separation zones. After the simulations and measurements in the wind tunnel, it was concluded that the winglet type 3 was the one that provided the greatest improvement in aerodynamic performance with a value of 4.54%.

With this improvement recalling Breguet's equations the improvement in the operating range of a UAV or keeping the range constant, there is a reduction in the specific fuel consumption with the same value.

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