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AERODYNAMIC OPTIMIZATION OF HIGH ASPECT RATIO WINGS FOR APPLICATION IN UNMANNED AERIAL VEHICLES (UAV'S)

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Abstract. *Recently, aircraft flying at high altitudes have become the center of attention of the academy and industry, as they have the potential to play the role that was once served only by satellites, such as monitoring, remote prospection and telecommunications. Unmanned aerial vehicles (UAV's) have lower operating costs and can conduct flight missions where they can take off and land at any time for equipment maintenance. This type of aircraft must have its endurance maximized to be able to remain in the air as long as possible. The reference for this paper is the AeroVironment Helios aircraft, that flew at more than 29,000 meters of altitude in 2001. Comparative studies are presented in order to evaluate the aerodynamic behavior of wings of different geometric parameters. The Multhopp method was implemented by the authors, to calculate the aerodynamic coefficients and loads on the wing. In this paper, the geometry of the wing is parameterized as a tapered shape with twist angle, keeping the same planform area. The results showed aerodynamic gains in terms of endurance and range. The results were promising for designing high aspect ratio wings to be applied in unmamed air vehicles (UAV's).*

Keywords: *wing, high aspect ratio, UAV, optimization*

1. INTRODUCTION

Recently, the increasing interest in the study and development of unmanned aerial vehicles (UAV's) has been contributing to the research and construction of new aircraft that make use of lighter materials, renewable energy sources and are able to stay for long periods in the air. Kozuba and Muszynski (2011) mention that these types of aircraft are capable of carrying out various missions, such as watershed study, border monitoring, fire detection in preserved areas, seismic and volcanic activities, agricultural mapping and telecommunications. The increasing demand for this type of mission has brought great advances for the operational deployment of these aircrafts (Meyer *et al*, 2009).

UAV'S can perform missions that were previously restricted to satellites (Morrisey *et al*, 2009). The great advantage in this case is that they have easier maintenance and can carry a large variety of loads. The fact that they can land and take off at any time facilitates to extend missions and data acquisition (Nickol *et al*, 2007)

In terms of performance, certain missions, such as monitoring and reconnaissance, require long operating times, in which the aircraft is able to stay as long as possible in the air. (Romeo *et al*, 2006) In this case, the endurance of the aircraft is a determining factor for achieving the objectives. Range can be evaluated when there are missions where it is necessary to fly from one point to another, traveling as far as possible. Aerodynamic and structural optimization of those aircraft can lead to considerable performance gains.

This work presents an aerodynamic and structural study of rectangular and tapered wings with twist, in order to find the geometry that has the best performance.

2. AERODYNAMIC AND STRUCTURAL CONCEPTS

For this work, aerodynamic and structural analysis are developed in order to calculate the wing performance. The aircraft performance depends on factors such as weight and aerodynamic coefficients (lift and drag) which provide information of the aerodynamic behavior to maximize the endurance or the range.

2.1 Aerodynamics analysis

The aerodynamic analysis involves the calculation of lift and drag to determine the flight performance. This work make use of the concepts provided by Anderson (2001) and Raymer (1992).

In rectangular wings, the chord length is constant along the wingspan. The ratio between the wingspan (b) and the mean geometric chord ($\bar{c}$) is the aspect ratio (AR), and defines the slenderness of the wing. The aspect ratio can be also calculated as function of the wing planform area (S), as established in Eq. (1) below:

$$AR \triangleq \frac{b}{\bar{c}} = \frac{b^2}{S} \tag{1}$$

For tapered wings, one important factor for sizing is the chord ratio (λ), which is defined as the ratio between the chord at the wing tip (C_T) and at the wing root (C_R), as shown in Eq. (2). In terms of design, it is recommended to use $\lambda \geq 0.2$ to avoid stall close to the wing tip (Raymer, 1992).

$$\lambda \triangleq \frac{C_T}{C_R} \tag{2}$$

In this paper, the calculation of the aerodynamic coefficients is performed by the Multhopp Method (Multhopp, 1950), which is known for its robustness and reliability when dealing with wings in low Mach number ($M \leq 0.3$) flows. From the airfoil data and wing geometry, it is possible to determine the C_L x C_D curve and with that the determination of maximum C_L/C_D and maximum $C_L^{3/2}/C_D$ conditions, leading to the maximum range and maximum endurance, respectively.

The drag coefficient can be calculated as the sum of the parasite and the induced drag coefficients, according to Eq. (3) below.

$$C_D = C_{Do} + C_{Di} \tag{3}$$

The shear and moment acting along the span can be estimated by the lift and mass distribution along the wingspan. In order to simplify the analysis, the payload is multiplied by the load factor (2.5g), according to CRF Part25 standard §25.337 (Federal Aviation Administration FAA Regulations).

2.2 Structural analysis

The spar sizing was performed by LISA® (LISA-Free FE Software), a Finite Element software. The concepts can be found in reference Zienkiewicz *et al* (2005). The structural analysis concepts can be found in Hibbeler (2010) and in Niu (1999). The spar was sized as an "I" beam profile (Fig. 1), and the thickness of the web and flanges (t_w and t_f, respectively) are kept constant along the wingspan. The spar height is a known function of the chord length (thickness to chord ratio of 0.137). Since the chord varies in a tapered wing, the spar height also vary along wingspan. The height dimensions were approximated considering assembly tolerances and future installations of panels and other structural components.

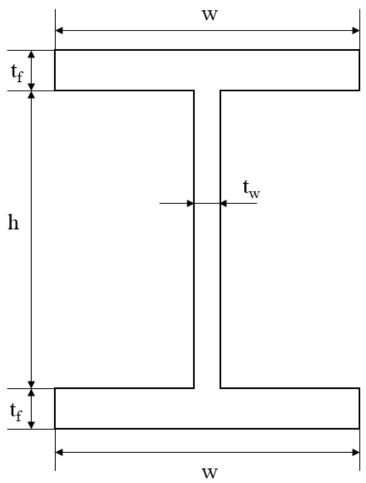

Figure 1. Spar "I" profile properties

The CFR Part25, §25.301, §25.303 and §25.305 (Federal Aviation Administration FAA Regulations) are used as the main criteria for structural analysis. As established in §25.305, the limit load applied can not result in permanent damage on the structure. Then, the maximum stress allowable is the material yield stress. The margin of safety is fixed in 10%.

2.3 Performance parameters

To reach optimal performance, the wing geometry and the angle of attack (with the respective velocity), must be optimized for maximum range and maximum endurance. The maximum range is obtained in conditions of maximum C_L/C_D. On the other hand, maximum endurance is obtained when $C_L^{3/2}/C_D$ is maximized. The endurance (T) and the range (d) can be calculated by Eq. (4) and Eq. (5), respectively:

$$T = E_a \sqrt{\frac{\rho S}{2W^3}} \left(\frac{C_L^{\frac{3}{2}}}{C_D} \right) \tag{4}$$

$$d = \frac{E_a}{W} \left(\frac{C_L}{C_D} \right) \tag{5}$$

E_a = batteries available power (kWh)
ρ = air density (kg/m³)
S = wing plan area
W = aircraft total weight (N)
d = distance traveled in meters (m)
T = time of flight (s)

The velocity (V) for maximum endurance and the respective angle of attack are those where $C_L^{3/2}/C_D$ reach the maximum value. On the other hand, the velocity for maximum range is that where C_L/C_D reach the maximum value.

3. OPTIMIZATION METHODOLOGY OF RECTANGULAR AND TAPERED WINGS

To keep consistency in the comparison between different wing shapes, the planform area was kept the same for all proposals. A reference aircraft is used as a guide to initial dimensions.

3.1 Reference aircraft and geometry parameters

The aircraft AeroVironment Helios was used as a reference for this work, since it is a pioneer UAV in flight at high altitudes and in use of photovoltaic cells as the main power supply. This aircraft was part of the NASA's Environmental Research Aircraft and Sensor Technology (ERAST) Project, and hit the altitude record in 2001 (29000 meters). Its wing has a rectangular shape, with 70 meters of wingspan and 30.9 of aspect ratio. The weight is approximately 930 kg, according to flight and mission requirements (Gibbs, 2017). Table 1 shows the geometric values used for the pre-sizing of the rectangular wing, all based on Helios (Hargreaves *et al*, 2018).

Table 1. Baseline wing characteristics.

Wingspan (m)	70
Chord length (m)	2.57
Planform area (m²)	180
Aspect ratio (-)	27.2 : 1
Empty weight (kg)	600

An aircraft weight estimative can be made, according to literature (Frágola, 2014): in an empty aircraft, 60% of the mass is due to solar apparatus and the other 40% are due to the structure itself, as spars (main structural component) and secondary parts (panels, trusses, stringers). Then, to calculate the wing spar mass, the following procedure can be made, as shown in Fig. 2 below.

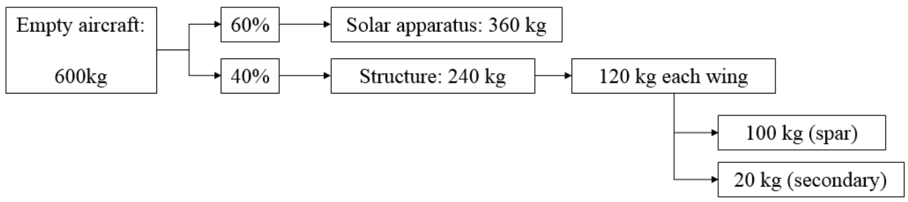

Figure 2. Mass considerations for the reference aircraft (empty)

The payload (corresponding to sensors, electronic equipment, etc) is approximately 330 kg, according to reference (Gibbs, 2017). Then, the aircraft gross weight (the sum of the empty weight and the payload) is 930 kg, according to Hargreaves *et al* (2018)

To calculate the solar aircraft performance, it is necessary to comprise the energy available in batteries. Since there is no information available about the battery capacities of the Helios, this work used the battery of Solar Impulse aircraft as a reference, which is a more modern aircraft, and it is assumed to have a more efficient energy storage capacity. In this case, it was estimated that the batteries have 85% of the payload weight, resulting in 280 kg. A proportional relation was used in order to estimate the battery capacity of the aircraft, according to Battery Bro (2015) as shown in Tab. 2.

Table 2. Aircraft battery storage estimative, according to Solar Impulse data

	Solar Impulse	Helios estimative (this work)
Battery weight (kg)	450	280
Battery capacity (kWh)	84	52.3

3.2 Mass estimative

For the wing analyzed, the spar is sized to meet the structural requirements. In order to reduce the analysis execution time, an estimation procedure was performed based on pre-sized spars, which serve as the basis for calculating all the others.

For three parts of the wing (root, middle and tip), the mass values were correlated according to the chord dimensions. Hence, it was possible to set up a mass database as function of the chords distribution along span and estimate the mass for different chord variations on each span. The mass estimative was obtained from preliminary calculations for some values of chord ratio leading to Eq. (6) below, where $x = \frac{2y}{b}$ correspond to the normalized (0 to 1) value of location in the wingspan (y) over the total wingspan (b).

$$m = \begin{cases} 130x^2 - 1060.6x + 2272.5 & 0 \leq x < 1/3 \\ 361.1x^2 - 1767.7x + 2272.5 & 1/3 \leq x < 2/3 \\ 3249.9x^2 - 5303.2x + 2272.5 & 2/3 \leq x \leq 1 \end{cases} \tag{6}$$

3.3 Designed wings proposals

The chord ratio was varied from 0.2 to 1.0, with a 0.1 step. The reason for this interval is that, according to the reference (Raymer, 1992), tapered wings with chord ratio less than 0.2 tend to stall close to the wing tip. This design factor was considered in this work. Considering a tapered shape, the wing planform area can be calculated by Eq. (7) below.

$$S = 2 \times \frac{(C_R + C_T)}{2} \times \frac{b}{2} = \frac{(1+\lambda)}{2} C_R \, b \tag{7}$$

Based on Eq. 11, it is possible to calculate the chord at the root (C_R) as function of the planform area (S), the chord ratio (λ), and the wingspan (b) as established in Eq. (8) below.

$$C_R = \frac{2S}{b \cdot (1+\lambda)} \tag{8}$$

The wingspan (b) and the chord ratio (λ) are the geometric parameters that can be optimized in order to result in the best performance configuration.

4. AERODYNAMIC AND STATIC ANALYSIS

The optimization of the tapered wings take as reference the optimal rectangular wing calculated in recent work (Hargreaves *et al*, 2018), whose results are reproduced as follows.

4.1 Aerodynamic

For the aerodynamic analysis, the airfoil chosen was the Liebeck LA2573A (Alemayehu *et al*) and it was originally installed in the Pathfinder aircraft (the predecessor of both Centurion and Helios). Its aerodynamic curves and geometry are available in the literature (Airfoil Tools Database).

Figure 3 below shows the airfoil profile for rectangular baseline wing, according to chord length.

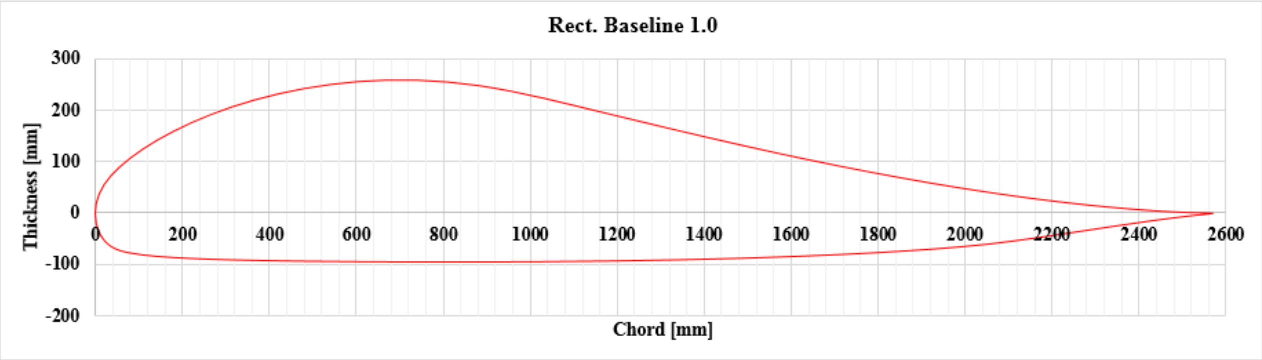

Figure 3. Airfoil profile for rectangular baseline wing

The spar height is delimited by the maximum thickness of the airfoil, as shown in Tab. 3.

Table 3. Baseline wing max. airfoil thickness.

b / b_{ref}	b (m)	C (m)	Max. Thickness (mm)
1.0	70.0	2.57	350

The airfoil and aerodynamic characteristics of the baseline rectangular wing are summarized in Tab. 4, as presented in Hargreaves *et al* (2018).

Table 4. Baseline rectangular wing aerodynamic characteristics.

Airfoil	LA2573A
$dC_L/d\alpha$ (1/rad)	6.68
Max. thickness/chord ratio (-)	0.14
Zero Lift Angle (°)	-0.88
CL Max 2D (-)	1.31
CL Max 3D (-)	1.26
Stall angle (°)	11.00

Figure 4 shows the lift distribution along the half span for the rectangular baseline wing, calculated using the Multhopp method (Hargreaves *et al*, 2018)

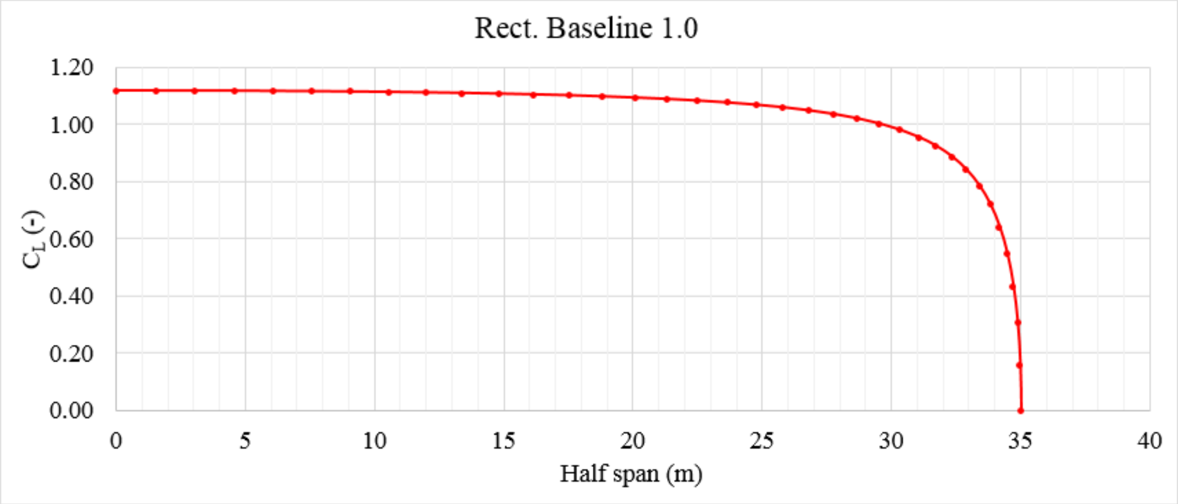

Figure 4. Lift distribution along half span

Table 5 shows the optimal parameters calculated for the rectangular baseline wing.

Table 5. Optimal parameters of the baseline wing.

Parameters	b / b_{ref}	Optimal Twist Ang. (°)	Optimal Ang. Attack (°)	C_L/C_D (-)	$C_L^{3/2}/C_D$ (-)
Max. Endurance	1.0	1.80	10.70	37.45	41.28
Max. Range	1.0	-1.80	9.80	40.86	39.79

4.2 Structural

For the static analysis, the geometric shapes were optimized to accomplish the analysis criteria. As a boundary condition, the spar was fixed at the center line of the aircraft in the six degrees of freedom. The spar material is the Aluminum T-2024 (Table 6), a very common alloy and widely used in the aerospace industry. This material has high strength/stiffness, good fatigue properties and isotropic behavior (Hargreaves *et al*, 2018)

Table 6. Aluminum T-2024 properties.

Modulus of elasticity (GPa)	73.1
Poisson's ratio (-)	0.33
Yield strength (MPa)	300.0
Tensile strength (MPa)	430.0
Density (kg/m³)	2800
Shear modulus (GPa)	28.0

The principles of solid mechanics were used for the stress analysis. The maximum height corresponds to the sum of the height of the web plus the thickness (t) of the two flanges. Table 7 shows the parameters of the optimal rectangular baseline and the results of the static analysis, previously presented in Hargreaves *et al* (2018).

Table 7. Baseline wing spar dimensions and static analysis.

b / b_{ref}	b/2 (m)	Mass (kg)	Max. height (mm)	Web height (mm)	Upper flange thickness (mm)	Lower flange thickness (mm)	Web thickness (mm)	Max. Displacement (m)	Max. Stress (MPa)	M.S.
1	35	125.6	320	300	10	10	1.5	12.1	273	0.1

5. RESULTS

The optimization of tapered wings for maximum endurance and maximum range considered the limit and accuracy established in Tab. 8.

Table 8. Variables domain optimized.

	Min.	Max.	Accuracy
b/b_{ref} (-)	1.00	1.25	0.01
λ (-)	0.20	0.90	0.10
Ang. At. (º)	0.00	11.00	0.10
Twist (º)	-2.00	2.00	0.10

Table 9 shows the results for optimal endurance and optimal range for wings flying at 10000 meters of altitude.

Table 9. Performance comparison of optimal baseline rectangular and optimal tapered wings.

	Baseline	Opt. Endurance	Opt. Range
b (m)	70.00	81.20	85.40
b/b_{ref}	1.00	1.16	1.22
Wing total mass (kg)	981.2	987.0	1032.0
λ (-)	1.00	0.20	0.20
C_R (m)	2.57	3.69	3.51
C_T (m)	2.57	0.74	0.70
Ang. At. (º)	10.80	10.50	10.20
Twist (º)	-0.90	1.40	1.80
Max. $C_L^{3/2}/C_D$ (-)	41.75	54.69	57.87
Max. C_L/C_D (-)	41.28	48.58	57.51
Max. Endurance (hh:mm)	14:10	18:24	18:04
Max. Range (km)	802	946	954

The results showed that, for a wing operating in conditions of maximum endurance, the optimal values are 81.20 meters for the wingspan (16% higher than the rectangular wing), 0.20 for the chord ratio and 1.40° for the twist angle. The calculated mass is 987 kg, which is about 0.6% higher than the baseline wing. For maximum endurance, the aircraft need to fly at 14.3 m/s with an angle of attack of 10.50°. This condition leads to a flight time of 18 hours and 24 minutes, which is approximately 30% higher than the rectangular baseline wing. This result represents an expressive gain in terms of performance for optimal endurance conditions.

For optimal range conditions, the optimal values are 85.4 meters for the wingspan (22% higher when compared to the baseline), 0.20 for the chord ratio and 1.80° for the twist angle. The mass increased by 5.18% (from 981.2 kg to 1032 kg). To operate in maximum range conditions, the angle of attack must be 10.20° and the velocity in this case is of 14.7 m/s. The maximum range achieved is 954 km, which represent an increase of approximately 19% when compared to the rectangular baseline wing at the same altitude. As in the previous wing, this result is relevant in terms of performance and efficiency gains.

For maximum endurance conditions, the travelled distance is 946 km, which is approximately 0.8% lower than the distance calculated for the wing optimized for maximum range conditions. The flight time calculated for the wing operating in maximum range conditions is 18 hours and 4 minutes, which is approximately 1.8% lower when compared to the maximum flight time calculated for the wing optimized for endurance.

Both results show that the optimization of tapered wings leads to gains in flight performance, when compared to the rectangular baseline wing, even when the operation is compared to the range in maximum endurance conditions and vice versa.

Figure 5 shows the wing planform of the final proposals in relation to the baseline rectangular.

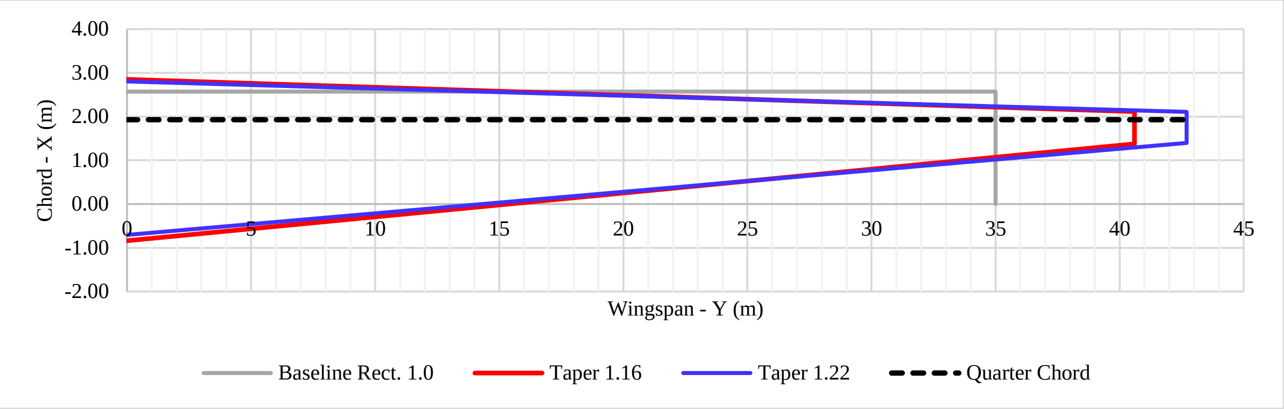

Figure 5. Wing shapes comparison between baseline and optimized tapered wings

The structural optimization lead to a new flange shape. Initially, the upper and lower flanges had the width constant along the wingspan. In order to relief weight, the flanges were optimized. Figure 6 shows the initial and final wing width shape along the wingspan.

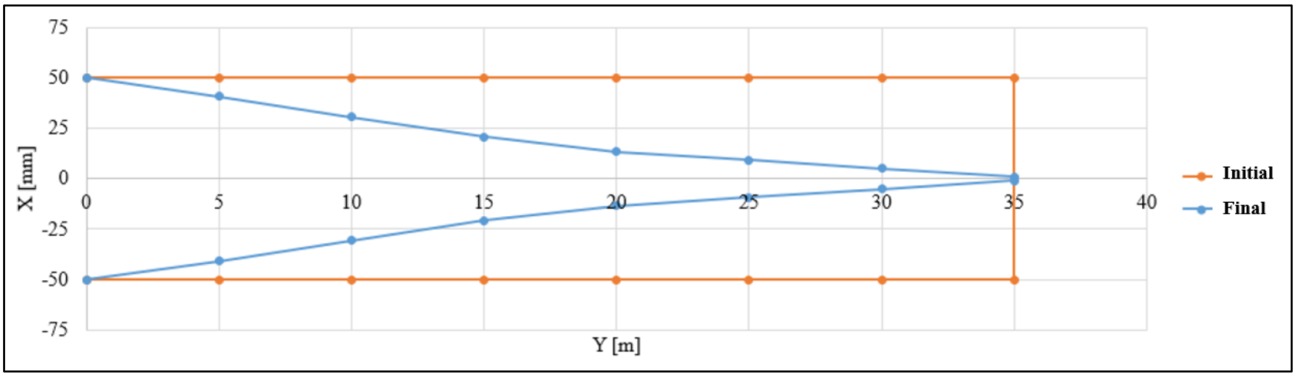

Figure 6. Spar top view; initial and final flange shape after the structure optimizing to weight relief

In order to evaluate the neighborhood of the optimal values, Fig. 7 and Fig. 8 shows the optimization results for maximum range and for maximum endurance conditions, respectively, compared to the reference rectangular baseline wing.

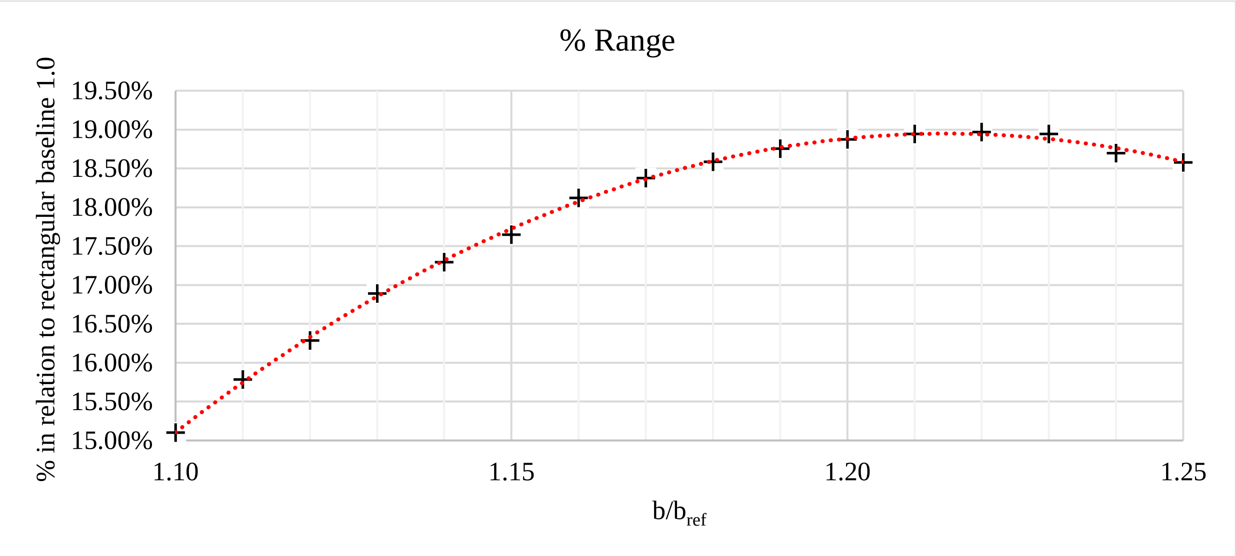

Figure 7. Range optimization

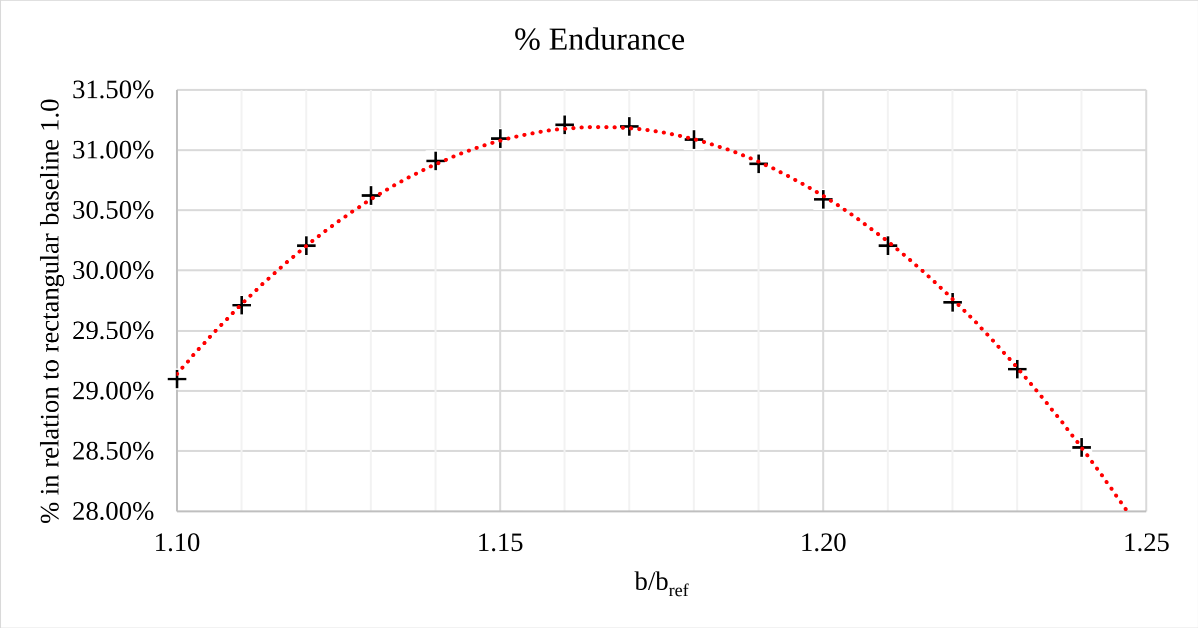

Figure 8. Endurance optimization

6. CONCLUSION

The results presented show that the adoption of tapered wings is advantageous in terms of aircraft performance, due to both, the increase on the lift coefficient and the reduction on the structural weight. The optimization showed that, the lower the chord ratio value (taper), the higher the performance coefficients for maximum range and endurance.

The structural weight of the wing is also a relevant factor, since the calculation of the performance is directly linked to the total weight of the aircraft. Wings with smaller chord ratio again leads to lower structural weight.

For both cases, range and endurance maximization, the minimum value chord ratio, λ equal 0.2, was the optimal value.

7. FUTURE WORK

For future work, it is intended:

Expand the optimization from tapered to the bi-tapered wing, by using two chord ratio for each wing and varying the point where the transition from one trapezoid to the other occurs.

In structural terms, design and calculate a torsion box for evaluation of the torsion phenomena in which the wing is subjected. The torsion box includes the structural reinforcement of the wing, across the design of skin panels, ribs and stringers.

In terms of performance, stipulate typical missions and maneuvers for high altitude UAV's and optimize performance, which leads to a wing that can be useful in various types of missions.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

Anderson, John, 2001. "Fundamentals of Aerodynamics". 3rd Edition, ISBN 0-07-237-335-0.

Alemayehu, D., Eaton, E., Faruque, I., "HALE UAV: AeroVironment Pathfinder". http://www.dept.aoe.vt.edu/~mason/Mason_f/pathfinder.pdf.

Airfoil Tools Database, information: <http://airfoiltools.com/>.

Battery Bro, 2015. "Batteries for electric airplanes: Solar Impulse II - flying across the Pacific". Information: <https://batterybro.com/blogs/18650-wholesale-battery-reviews/31850627-batteries-for-electric-airplanes-solar-impulse-ii-flying-across-the-pacific>.

Federal Aviation Administration (FAA) Regulations. Information: <https://www.faa.gov/regulations_policies/faa_regulations/>.

Frágola, Luciano M., 2014. “Development Of A Conceptual Design Methodology Focused On Solar Aircrafts”. M.Sc. Thesis, Universidade Federal de Minas Gerais, Belo Horizonte/Brazil

Gibbs, Yvonne, 2017. “NASA Armstrong Fact Sheet: Helios Prototype”. Information: <https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-068-DFRC.html>.

Hargreaves, Bernardo O., Utsch, Ricardo L., Frágola, Luciano M., 2018. “Design Study of High Aspect Ratio Wings for Unmanned Air Vehicles (UAV’s)”. SAE Technical Paper 2018-36-0073.

Hibbeler, R. C.,“Resistência dos Materiais”. São Paulo: Pearson Prentice Hall,2010, 7th Edition, ISBN 9788576053736.

Kozuba, J., Muszynski, T., 2011. “Design Concept of a Low-Cost, Long-Endurance Unmanned Aerial Vehicle”. Transactions Of The Institute Of Aviation. ISSN 0509-6669.

LISA-Free FE Software, information: <https://lisafea.com/>.

Meyer, J., Plessis, F., Clarke, W., 2009. “Design Considerations for Long Endurance Unmanned Aerial Vehicles”. Aerial Vehicles IntechOpen, DOI: 10.5772/6482.

Morrisey, B., McDonald, R. “Multidisciplinary Design Optimization of an Extreme Aspect Ratio HALE UAV”. 2009. 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO). USA.

Multhopp. H., 1950. “Methods for Calculating the Lift Distribution of Wings (Subsonic Lifting-Surface Theory)”. Reports and Memoranda No.2884, United Kingdom.

Nickol, Craig L., Guynn, Mark D., Kohout, Lisa L., Ozoroski, Thomas A., 2007. “High Altitude Long Endurance UAV Analysis of Alternatives and Technology Requirements Development”. 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno/NV, United States.

Niu, Michael C., 1999. “Airframe: Stress Analysis and Sizing”. 2nd Edition, Hong Kong Conmilit Press Ltd, ISBN: 96271280802.

Raymer, Daniel P., 1992. “Aircraft Design: A Conceptual Approach”. American Institute of Aeronautics and Astronautics, 2nd Edition, ISBN 0-930403-51-7.

Romeo, G., Frulla, G., Cestino, E., 2006. “Design of a high-altitude long-endurance solar-powered unmanned air vehicle for multi-payload and operations”. Department of Aerospace Engineering. Turin Polytechnic University. Corso Duca Abruzzi. Turin, Italy.

Zienkiewicz, O.C., Taylor, R.L., Zhu J.Z., 2005. “The Finite Element Method: Its Basis and Fundamentals”. 7th Edition. ISBN 0750663200.

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