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STUDY OF THE COMPROMISE OF AERODYNAMIC AND STRUCTURE STANDPOINTS IN A HIGH-ASPECT RATIO WING DESIGN

Luciano Magno Fragola Barbosa* , Ricardo Luiz Utsch de Freitas Pinto*, Bernardo Oliveira Hargreaves*, Lapo Gori*
*** UFMG, Universidade Federal de Minas Gerais. Brazil**

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Abstract

In this work high aspect-ratio straight-trapezoidal wing planforms are analyzed, considering both aerodynamic and structural standpoints.

The wings are analyzed as candidates to be used in a low-speed, very-low wing loading, solar aircraft. The motivation for the straight-trapezoidal wing planform geometry is to obtain a simple geometry to allow a feasible construction and installation of a solar array in its upper surface; and at the same time presenting low induced drag coefficient, in comparison with a rectangular wing of the same aspect ratio.

The intermediate goals of the analysis are: In terms of aerodynamics, to obtain the trends of induced drag coefficient related to geometric proportions for a given aspect ratio; and in terms of structures, to define the trends of wing structural mass and wing main vibration modes, related to the variations on the wing geometry, for a given aircraft mass and design load factor.

These intermediate features are the basis for the main goal - to obtain the best compromise between aerodynamics and structures, in terms of wing planform. The overall process starts with the evaluation of induced drag coefficients and the lift distributions for the given planforms. From this analysis, several different geometries are defined for the same induced drag. And the lift distributions – together with the aircraft mass values and the airfoil pitching coefficients – are the inputs for the load analysis, i.e. the definition of the spanwise distribution of bending and torsion moments. From these loads the sizing of the wing spar and torsion box is performed. And from this sizing, the structural masses, vertical displacements in flight, and modes of vibration, are defined for each planform considered.

The induced drag coefficients and the lift distribution are obtained through a routine made by the authors based on the lifting line approach. The vertical displacements in flight and the modes of vibration are obtained by means of finite element analysis. The main results from this study are: The comparison, among the planforms analyzed, of the wing spanwise deformation, the wing modes of vibration, the wing structural masses; and the wing planform geometry chosen as the best compromise.

1 Introduction

This work is the step ahead of the analysis previously performed by the authors [1] of the advantages of an elliptic planform compared with a rectangular wing, regarding both aerodynamics [2] and structural [3] standpoints.

The previous analysis encouraged this work, in which the potential advantages of a straight-trapezoidal wing planform (partilally a rectangular wing, in the inboard portion, and partially a tapered wing, in the ouboard portion) compared with a rectangular wing - i.e. presenting a constant chord along span – are investigated, also from both aerodynamics and structural standpoints. Although the elliptic wing represents a good theoretical reference for studies, and the rectangular wing can be the best in terms of constructive aspects, the straight-trapezoidal wing –since well investigated and well defined - could be a god compromise between both planforms.

The straight-trapezoidal wing, although being more complex constructively than the purely rectangular wing, can be much easier to build than an elliptical one, and could present aerodynamic and structural features, if well defined, very close to the elliptical wing.

These aspects are the main motivation for the present study. So in this study a straight-trapezoidal wing planforrn is defined to have the same area and induced drag of a existing, already-flown, rectangular wing, and the advantages related to the rectangular wing – if they exist - in terms of structural mass and structural stiffness of this straight-trapezoidal wing planforrn are investigated, quantified and also compared to the advantadges - already known [1]- of the elliptical wing.

2 Methodology

The general analysis procedure developed in this work is a development of the initial procedure created by the authors as shown in the reference [1]. This work can be considered as the next step after that one, and the main improvements are the consideration of a straight-trapezoidal wing instead of an elliptic geometry, and the analysis of the torsion box additionally to the main spar analysis. The main steps of the present analysis are:

- Definition of an aircraft with high aspect-ratio wing, and rectangular wing shape, to be used as the baseline;
- Definition of the 'best' straight-trapezoidal wing with the same area and induced drag of the baseline wing: the geometry that allows for the lowest aspect ratio for the same induced drag;
- Definition of the design flight loads for the two wings: lift distribution, and torsion moment mainly;
- Structural sizing for the two wings: spar and torsion box;
- Evaluation of the masses of spar and torsion box for the two wings;
- Determination, by means of finite element (FE) methods, of vertical displacement of the spars when subjected to the limit flight loads, and modes of vibration of the spars;
- Comparison of main features of the two wings: structural masses; displacements due to the flight loads.

3 Reference Aircraft

The reference aircraft adopted for this study is, as the previous work [1] the NASA-Aerovironment Helios aircraft. This pioneer aircraft, with rectangular wing, wingspan of 75.3 m, aspect-ratio of 30.9, had been used in researches of high-altitude, sun-powered flight missions [4]. Its wing has been defined as rectangular-shaped due to constructive reasons. In terms of span, it is the largest already-flown flying wing. The aircraft general arrangement is shown in Figure 2. In the figure, wings are bent upwards due to flight loads. On the ground, wing dihedral is close to zero.

Figure 1 – Helios Aircraft, from [3]

4 Aerodynamic and Load Analysis

Along this study, several plots are presented adopting the axis along wing semi-span as abscissa; starting from the aircraft symmetry plane – i.e. the aircraft centerline. The wings considered have no sweepback, washout and dihedral. The coordinate system adopted for the wings analyzed is X positive backwards, Y positive to right hand-side, Z positive upwards.

The lifting-line approaches [5] as Multhopp method [2] are well-known means of obtaining both spanwise lift distribution and induced drag factor for a given wing planform, and have been an usual tool for aircraft design and analysis. The Multhopp method, due to its robustness and reliability, has been adopted for the aerodynamic analysis of the present work. From the method theory [2] [5], a dedicated computer code has been made in order to perform the aerodynamic analysis for this work. The goal for the aerodynamic analysis is to obtain a straight-trapezoidal wing with same area and same induced drag of the rectangular baseline wing. The lifting-line model used 129 discrete vortex line elements along wing span, placed in a cosinusoidal spanwise distribution. The two types of geometry, rectangular and straight-trapezoidal, have been evaluated though the Multhopp approach, in order to allow a induced drag comparison based on the same method. Several straight-trapezoidal wings have been evaluated in order to determine the one with induced drag the closest of the one from the baseline wing. For the wings evaluated, the angle of attack is fixed in 0.1 radian, and an airfoil with a two-dimensional lift curve slope ($CL\alpha$) of 6.0 per radian is considered.

In searching for the best planform a iterative procedure has been performed. The best straight-trapezoidal planform is considered as the one with the lowest span for the same induced drag of the rectangular wing. The parameters to be varied are the overall span, the span of the rectangular portion of wing the taper ratio – i.e., the ratio between the tip chord and the root chord. From the formulation presented in [2], [5], the induced drag coefficient of the reference rectangular wing is defines as $0.0127/CL^2$. The straight-trapezoidal wing with the same induced drag and the lowest span is found as having the span of 68.54 m, the root chord of 3.245 m, the tip chord of 0,974 m, and the aspect ratio of 25.6. The comparison between upper view of the two wings - the baseline rectangular wing and the corresponding straight-trapezoidal wing obtained - is presented

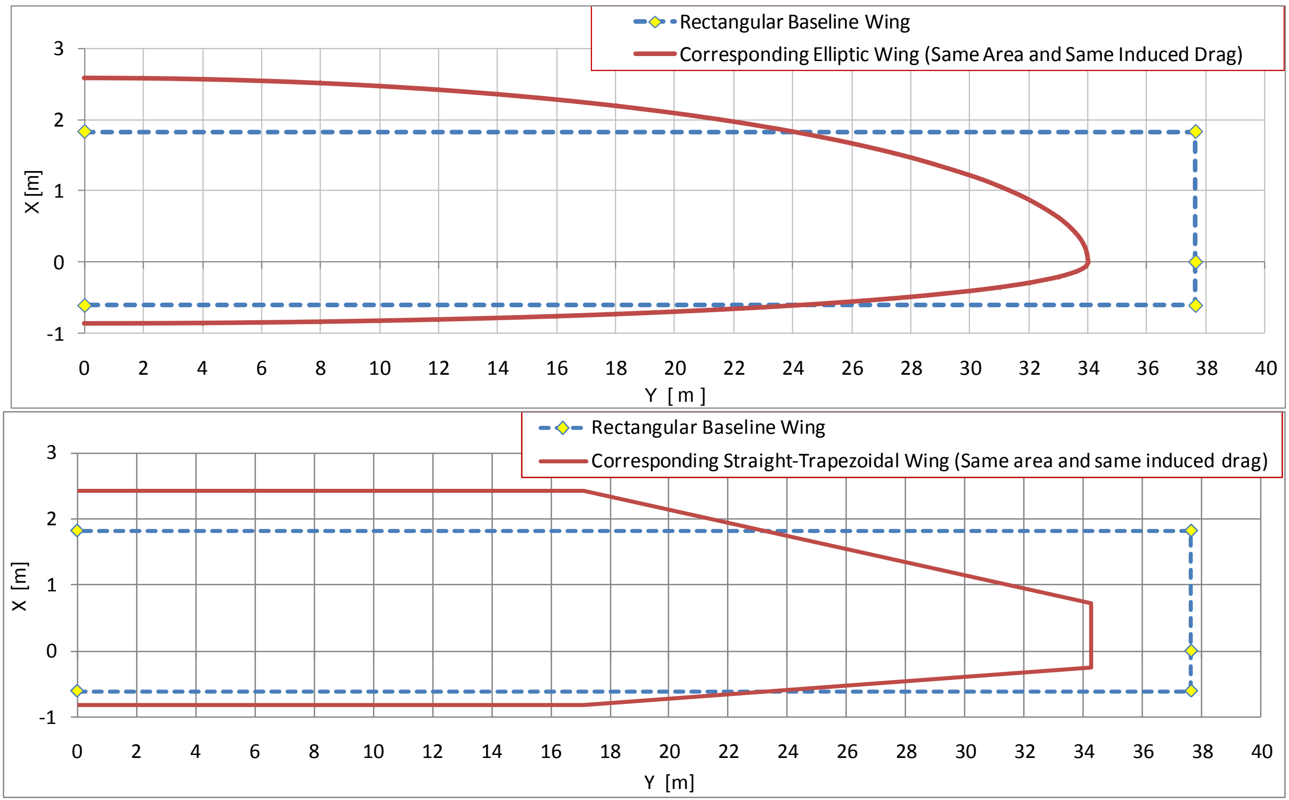

Figure 2 – Chord distribution along span

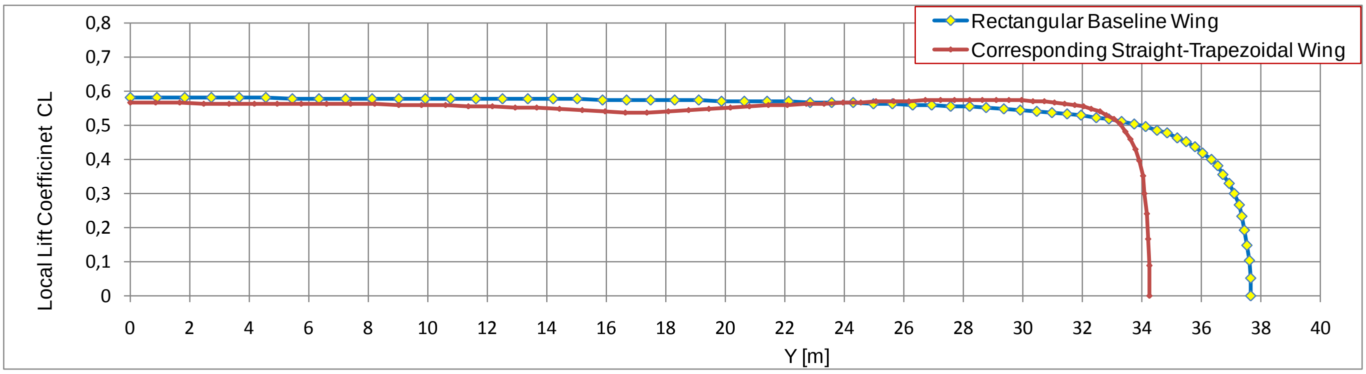

Figure 3 – Local lift coefficient CL along span

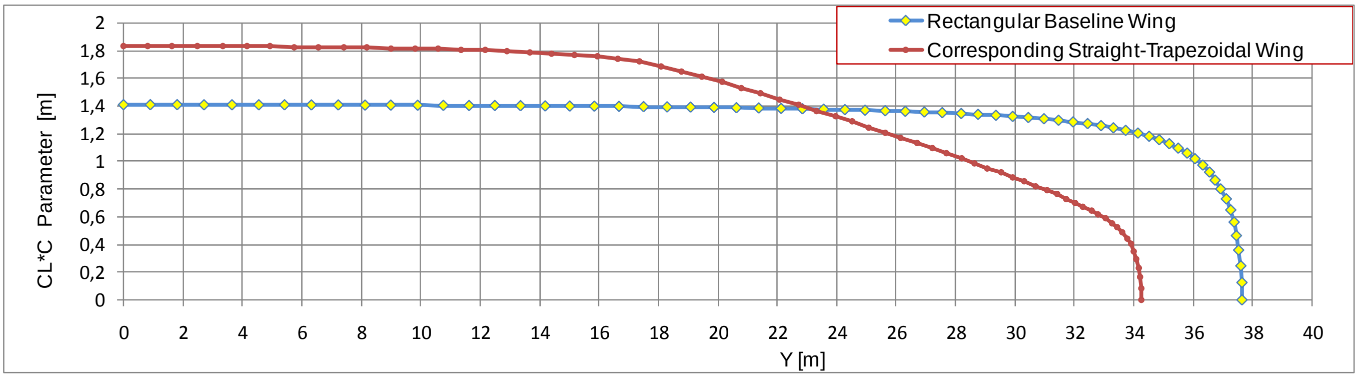

Figure 4 – Loading parameter 'CL * C' along span

in Fig. 2. The area of both wings is 183.5 m^2. It can be noticed from Fig. 2 that the straight-trapezoidal wing, compared to the rectangular wing, presents a 9% smaller span and a 33% larger root chord (at Y=0). Both aspects are beneficial for the straight-trapezoidal wing in terms of structure. For comparison purposes, a elliptic wing with the same area and same induced drag [1] is also shown in Fig. 2.

The distributions of lift coefficients for the two wings – rectangular and straight-trapezoidal – obtained from the Multhopp approach [2], are presented in Fig. 3. From this information, the distributions of the loading parameter 'lift coefficient times chord' (CL*C) for the wings are presented in Fig. 4.

From these distributions - and estimating the aircraft total mass, the mass distribution and the design limit load factor - it is possible to define the diagrams of shear force and bending moment along the wing span [3], presented in Fig. 5. The aircraft mass distribution is taken from [4] and [6]. A simplifying assumption is taken, in terms of load analysis, which is to consider the influence of mass items distributed along span – solar panels, propellers, engines, wing pods - negligible for the wing bending moment, when compared to the central payload pod, attached to the wing at Y=0. This assumption is consistent with the one of the guidelines of the Helios design, which was to distribute the masses as equally as possible along span [4]. Apparently this has been achieved except by the installation of the central payload pod. The mass of this pod is considered as 330 kg [4] [6]. The limit flight load factor is defined as 2.5g, considering that this aircraft is destined to special missions, and taking CRF Part25, §25.337 [7] as the flight load requirement. The shear force at y=0 from each wing side is 4045 N.

The torsion loads are obtained considering a hypothetical pitching maneuver in which the movable control surfaces, supposed to be at the trailing edge of the wing along its full span, are deflected downwards, resulting in a pitching moment of -0.1 related to the point of 25% of the chord. The speed adopted for this maneuver is100 km/h equivalent airspeed, i.e., at the conditions of air density of 1.225 kg/m^3. The resulting torsion moment distribution about the point of 25% of the chord, for both wings, is presented in Fig 6.

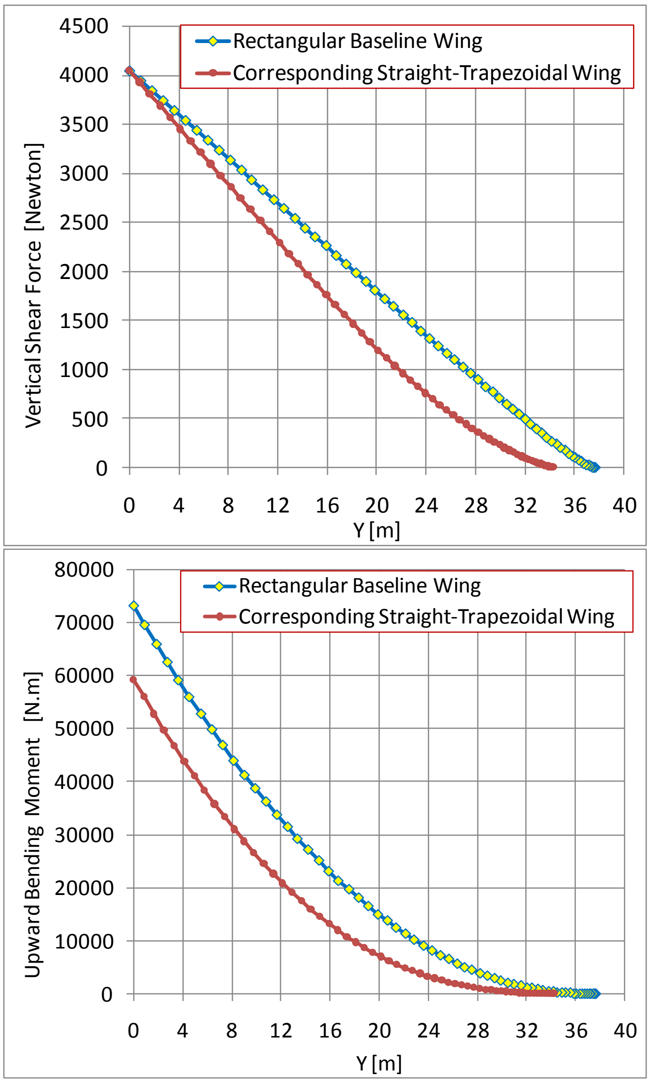

Figure 5 – Shear Forces and Bending Moments along Span, Limit Flight Condition

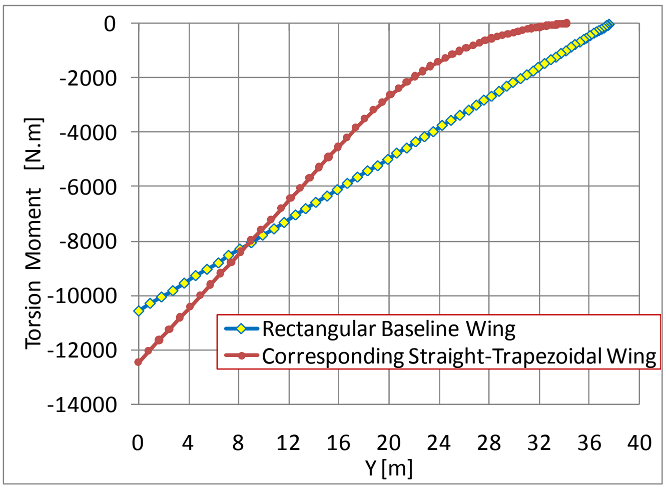

Figure 6 – Torsion Moments along Span

5 Structural Sizing and Analysis

The structural items considered are the main spar and the torsion box.

The main spar of the wings is considered as follows. The adopted material for this study is the T-2024 aluminum alloy. The adoption of this material – different from the composite materials used in spars of high aspect ratio aircraft - is motivated by its isotropic characteristics, which allow this analysis to be more reliably checked. The spar is adopted as being an 'I'-shaped section, with variable width (B) along span, and – for easiness of analysis and understanding – constant thicknesses: 0.010 m for caps and 0.0015 m for the shear web. The local height (H) of the spar is taken as the 13.5% of local wing chord minus 0.024 m to account for the thicknesses of wing skin and solar panels. The local width of the spar is defined to comply with the limit loads already defined, and considering that the limit local stress does not surpass 300 MPa. The whole aircraft spar (both left and right sides) masses are: 210 kg for the rectangular wing, and 153 kg for the straight-trapezoidal wing. These two numbers indicate a first advantage of the straight-trapezoidal wing: The spar of a straight-trapezoidal wing - which has the same drag, withstands the same aircraft mass at the same flight load factor - is appreciably lighter than the one of the rectangular wing.

At this point of the study a third wing spar is included: the 'straight-trapezoidal wing 2' which corresponds to the same straight-trapezoidal wing geometry – and corresponding loadings – but presents a reinforced spar by means of a increasing in the caps width, in order to achieve the same mass of the rectangular wing spar. The schematic arrangement of the three spars: of 'rectangular wing', 'straight-trapezoidal wing' and 'straight-trapezoidal wing 2' are shown in figure 7. The values of H and B for the spars of 'rectangular wing' and 'straight-trapezoidal wing' are presented in Fig. 8.

Once defined the geometry of the three spars, a linear FE analysis has been performed by means of two different softwares, LISA [8] and Insane [9]. LISA, or Lisa-Free 8.0.0 is a user-friendly finite element analysis package for

Windows with an integrated modeler, multi-threaded solver and graphical post-processor. The software INSANE (INteractiveStructural ANalysis Environment) is an object-oriented open-source software for structural analysis, developed by the structural engineering department of the Federal University of Minas Gerais. The FE analysis have been performed in order to obtain:

- The vertical displacements of the wing, when subjected to the limit loadings;
- The frequency of the spars vertical bending vibration mode, considering and the wing mass distribution. A consistence check is also performed by evaluating the vibration modes related to the spar mass values-only.

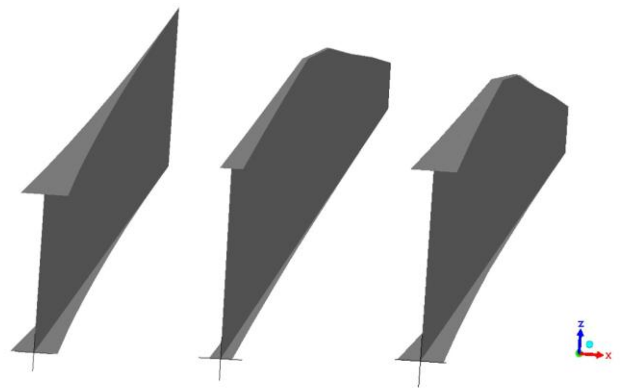

Figure 7 – Arrangement of the Spars: Rectangular wing (left), straight-trapezoidal wing (center) and straight-trapezoidal wing 2

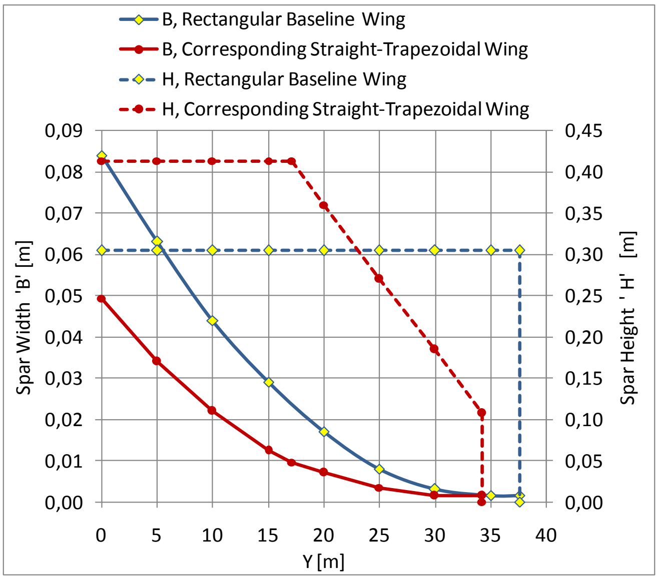

Figure 8 –Width and Height of Wing Spars

The torsion box is sized in considering the torsion moment distribution and also adopting the adopted material for this study as the T-2024 aluminum alloy. The thickness of the torsion box walls is sized to comply with the limit torsion loads defined, and considering that the limit shear stress does not surpass 150 MPa. The geometry of the torsion box is defined according three critera: to allow for easy construction, to present constant thickness walls along span, and to be sized according to the torsion loads. The geometry obtained for the torsion box is presented in Figures 9 and 10. The geometry in Fig. 10 is presented terms of dimensions X and Y divided by the 'center line' (at Y=0) chord CR. Due to the large space available to the torsion box, the – constant - thickness of the wall is found to be very thin, about 0.25 millimeters.

The masses obtained for the torsion box of the whole aircraft (left plus right sides): 41 kg for the rectangular wing, and 31 kg for the straight-trapezoidal wing. Also as for the spar, the torsion box of straight-trapezoidal wing is lighter than the one of a rectangular wing for the same flight conditions.

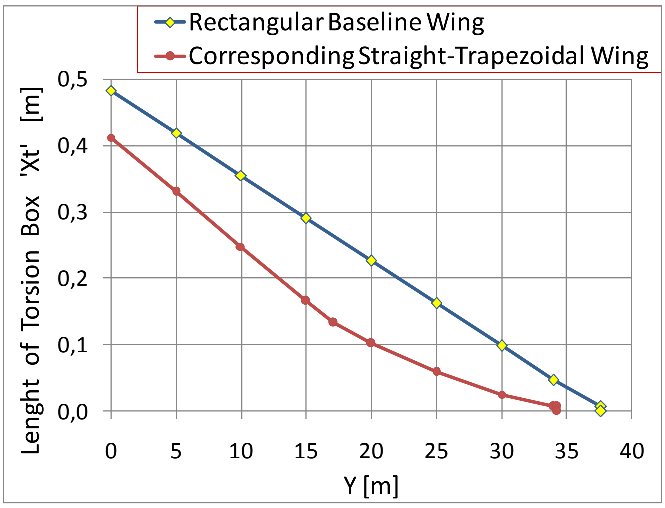

Figure 9 –Length of Wing Torsion Boxes

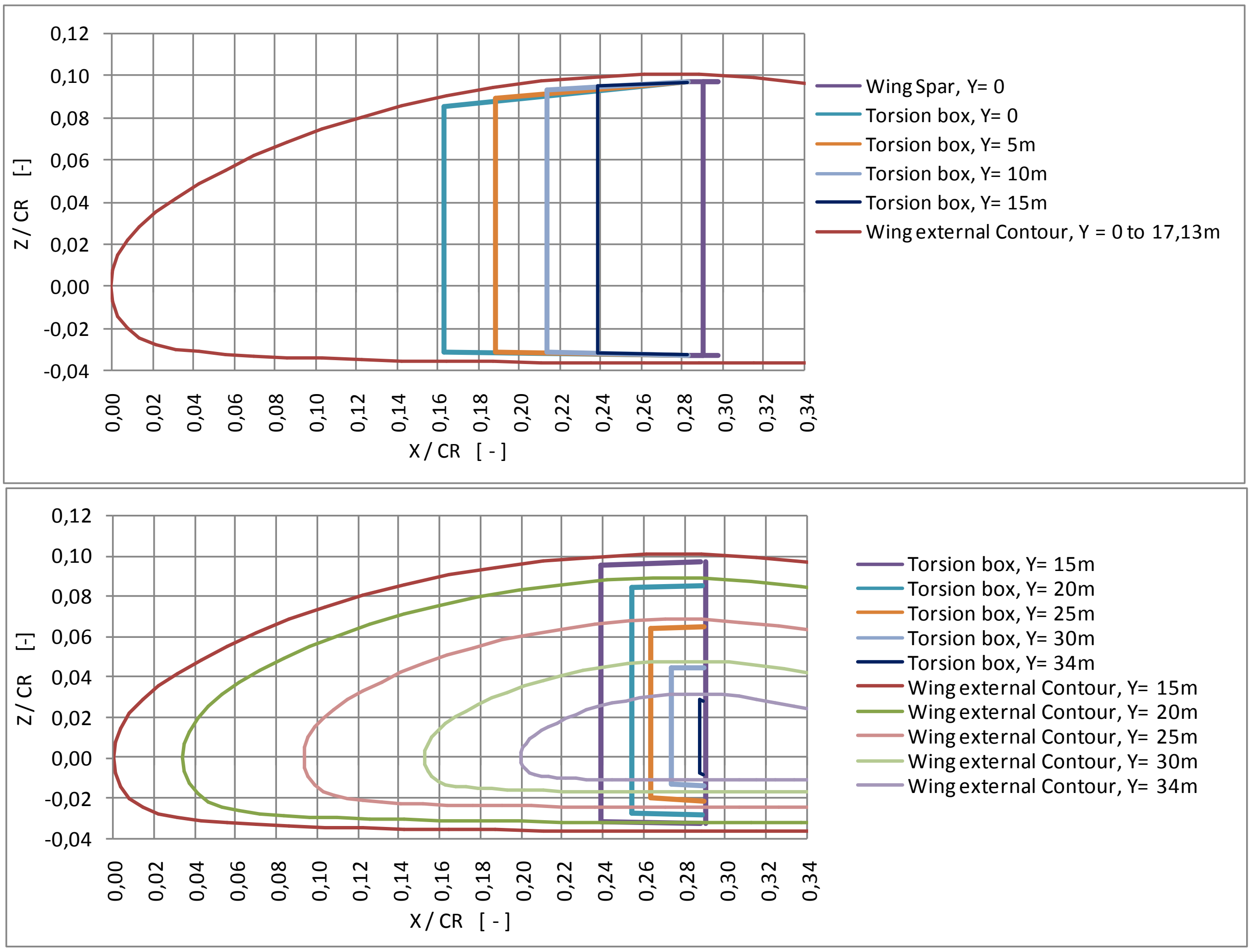

Figure 10 –Side View of the Torsion Box Sections along Span

6 Results

The main results are the comparisons between vertical displacements of the wing, the frequencies of the vibration modes and the masses of the spars and torsion boxes.

The vertical displacements of the wing spars, when subjected to the limit flight loads, and the structural mass obtained for the spars, both shown in Fig. 11. The comparison between rectangular wing and straight-trapezoidal wing , in terms of mass of main structural items – spar and torsion box – is presented in Fig. 12.

The vertical displacements in the wing tips of the rectangular wing, the straight-trapezoidal wing and the 'straight-trapezoidal wing 2' are compared in Fig.13. The frequency of the vertical bending vibration modes of the wings, obtained from the FE method are also presented in Fig. 13.

From Figs. 11 and 13 it can be noticed that the tip displacements of the straight-trapezoidal wing are significantly lower than the one from the baseline rectangular wing: For a 27% lighter spar, the displacement is 47% lower, and for a spar with the same mass than the rectangular one, the displacement is 68% lower. Additionally, the natural frequencies of the spars of the straight-trapezoidal wings are also benefited, achieving higher frequency values: for a 27% lighter spar, the frequency of the vertical bending mode is 44% higher, and for a spar with the same mass than the rectangular one, the frequency is 84% higher.

In Fig. 14 the values obtained from for a straight-trapezoidal wing are compared to the ones presented in [1], for a elliptic wing also equivalent in area and induced drag to the same reference rectangular wing. Comparing these results ne can note that the straight-trapezoidal

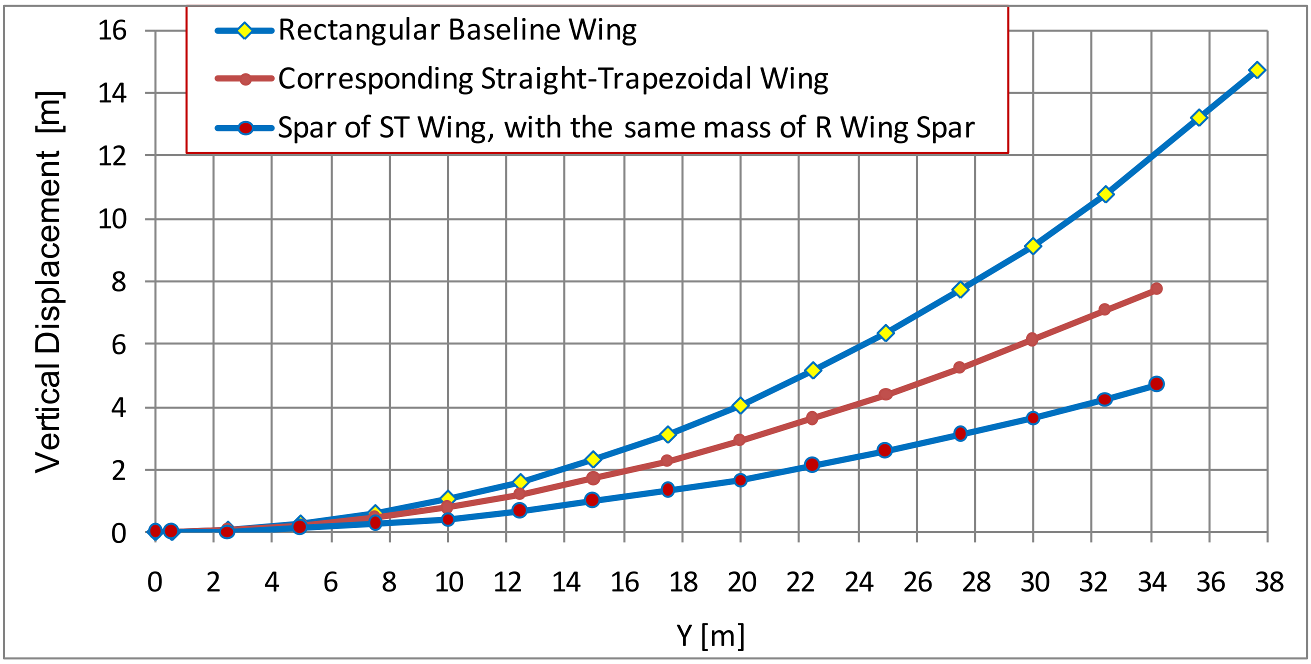

Figure 11 – Comparison of vertical displacements at limit load

wing as roughly as advantageous - in terms of both displacements and structural mass - as the elliptic wing.

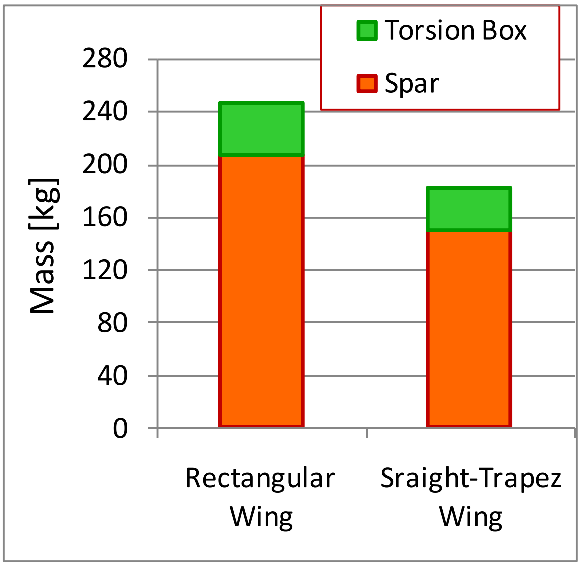

Figure 12 – Masses of Spar and Torsion Box

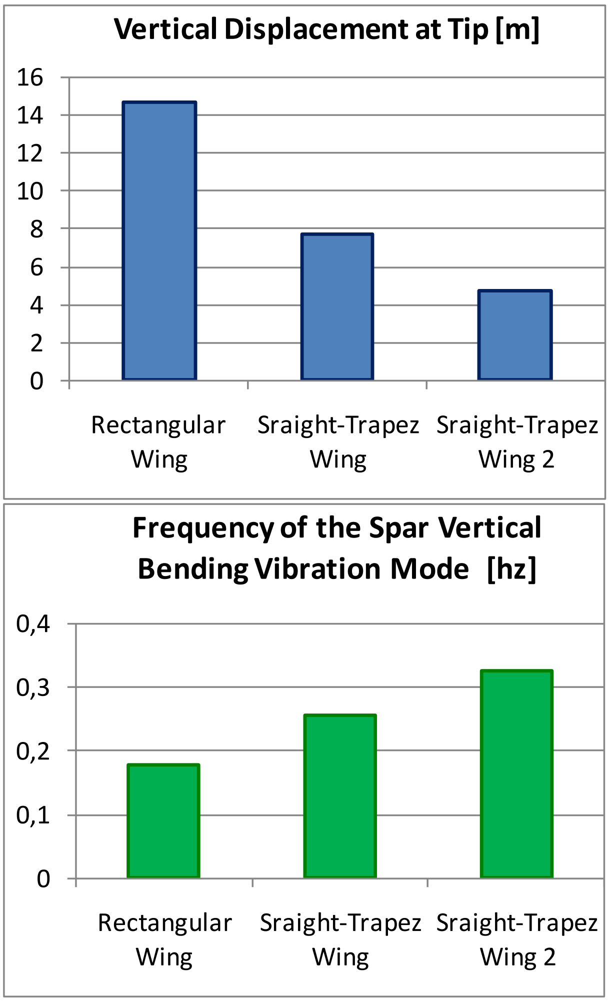

Figure 13 – Comparison of Tip Displacements and Bending Mode Frequencies

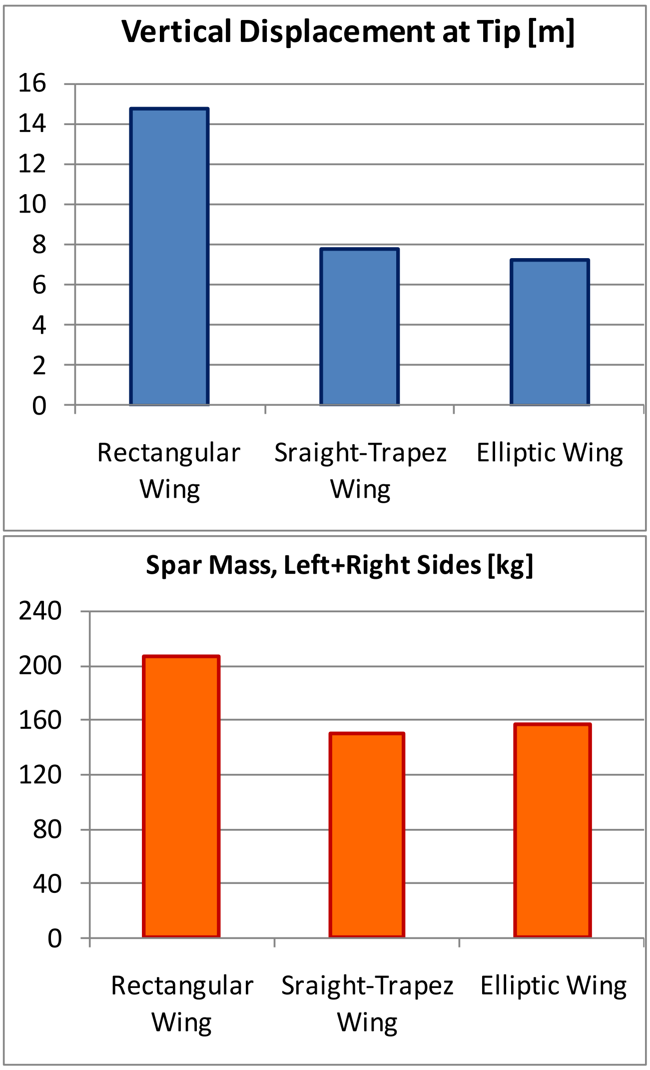

Figure 14 – Comparison between Rectangular, Straight Trapezoidal and Elliptic Wings

7 Conclusion

The adoption of a straight-trapezoidal wing, aerodynamically equivalent to a baseline rectangular shape, can result in vertical displacements significantly lower and natural frequencies higher than the ones from the baseline wing. For high aspect-ratio wings, in which high vertical displacements and bending frequencies can be a challenge, the adoption of wings with straight-trapezoidal planforms can be a valuable solution from both aerodynamic and structural standpoints. In addition, the straight-trapezoidal wing is almost as advantageous as an elliptic wing in replacing a rectangular wing with the same drag and area.

Considering the good constructive features of a straight-trapezoidal wing related to a elliptic one, a correctly sized straight-trapezoidal wing can be a good compromise, in both aerodynamic and structural standpoints, for new designs of very light and high-span aircraft such as solar aircraft. The results obtained keep encouraging the authors to continue the development of the methodology presented in this work.

8 Acknowledgments

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10 Contact Author Email Address

Mail to:

luciano.fragola@gmail.com,
utsch@demec.ufmg.br,
bernardo.oliveirah@gmail.com,
g.lapo@gmail.com

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