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## PARAMETRIC DRAG ANALYSIS OF STRUT BRACED WING AIRCRAFT FOR REGIONAL AVIATION

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**Abstract.** *The conventional configuration of commercial aircraft composed by a tube fuselage, a cantilever wing, a vertical and a horizontal tail, has been improved since its introduction in the 1950s, and it is unlikely that big improvements should occur without drastic changes. The strut braced wing aircraft presents itself as an option. The main difference lies on a strut connecting the wing to the fuselage, reducing the bending moment of the wing and, consequently, its weight. Alternatively, the weight could be maintained constant while the wing span is increased and the wing thickness is decreased. This combination of geometric changes reduces drag and improves performance. A drag breakdown comparison is performed between the strut braced wing and the conventional aircraft configurations, based on a regional aviation mission. Parametric drag analyses on the strut braced wing configuration are conducted. Drag reductions of 12% are obtained when comparing the strut braced wing against a conventional aircraft of similar size, and 36% when comparing a high aspect ratio strut braced wing against a conventional aircraft.*

**Keywords:** *strut braced wing, drag, regional aviation*

### 1. INTRODUCTION

The configuration of commercial transport aircraft has not changed significantly since the introduction of the Boeing 707 in 1957. In order to improve the performance of this type of transport, some advances have been made contemplating propulsion, systems, aeronautics and structures. However, the cantilever wing configuration, with variations on the position of the wing relative to the fuselage, variations of the horizontal tail relative to the vertical tail and variations on the engine position, has dominated the design scenario. Furthermore, it is unlikely that big improvements in performance will occur without a change in aircraft configuration.

NASA studies (NASA, 2014) on future trends for improvement of the aircraft industry indicate that “wings for future aircraft will be of higher aspect ratio, lighter and more elastic than today”. To achieve higher aspect ratios, the strut braced wing (SBW) aircraft configuration might be a solution. It has many similarities with the cantilever configuration. It consists of a fuselage with a wing, and a horizontal and vertical tails. However, there is a strut that connects the wing to the fuselage, to alleviate the wing bending load. This allows the span of the wing to be increased, without weight penalties, and, consequently its aspect ratio is increased, reducing induced drag. The strut also allows the wing thickness to be decreased, diminishing the profile drag and the transonic wave drag, allowing the wing to unsweep. A less swept wing and the smaller chord Reynolds number provide more areas of natural laminar flow, reducing parasite drag. The total reduction in drag is expected to improve significantly the performance of the SBW aircraft when compared to the cantilever wing configuration. Furthermore, as contemplated by Gundlach IV, et al. (2000), the SBW is likely to have a more favorable reaction from the public than other unconventional configurations since there is little to distinguish the SBW from the existing airliner fleet, just the high wing and a strut.

Studies were conducted by Meadows, et al. (2012), Carrier, et al. (2012) and Barreda (2013) on this configuration for aircraft such as the Boeing 777, Boeing 737 and Airbus A320, however not much information is available for regional aircraft. Regional aviation is an important market and service in society nowadays. It is responsible for

connecting emerging cities and the countryside to the central areas, in short- and medium-haul distances. Since demand tends to be lower for these routes and to require more frequent flights due to their shorter distance, smaller aircraft are known to be more lucrative for the operators. Smaller aircraft cost less per trip and can be filled easier.

The earliest recorded studies on SBW date back to the 1950s, when Werner Pfenninger at Northrop idealized a transonic transport aircraft for a long range mission. Pfenninger realized that to obtain an efficient airplane, the induced drag had to be reduced to nearly the value of the parasite drag, and this was possible with wings of high aspect ratio.

More recently, Grasmeyer (1998) studied the SBW aircraft through Multidisciplinary Design Optimization (MDO), with the objective to analyze and quantify the possible improvement in performance of transonic commercial aircraft at a conceptual level. The Boeing 777-200IGW mission profile was chosen for the analyses and the SBW configuration was optimized for minimum takeoff gross weight. The optimized SBW showed a 15% decrease in takeoff gross weight, 29% reduction in fuel weight, 28% increase in aerodynamic efficiency  $L/D$  and 41% increase in seat-miles per gallon when compared to a conventional cantilever optimized configuration.

Gur, et al. (2010) performed a sensitivity study on various aerodynamic parameters of the SBW configuration. It was observed that the airfoil selection is a critical point in the design, because it influences directly on the natural laminar flow, the supercritical characteristics, the high lift and low drag coefficients.

Meadows, et al. (2012) analyzed a medium range aircraft of the size of the Boeing 737-800NG through MDO and obtained a 47% reduction in fuel consumption of the optimized aircraft when compared to the current aircraft.

Barreda (2013) evaluated the potential of the SBW configuration for a passenger aircraft similar to the Airbus A320 through MDO and obtained a 33% reduction in fuel consumption for the optimized SBW when compared to an optimized A320.

Most of the studies were conducted using MDO as a tool. This method is interesting because it captures the great synergistic features, that might not be so obvious to the engineering mind, of the SBW configuration due to the strong interdependency of structures, aerodynamics and propulsion. However, the results are dependent on the accuracy of the models for the several disciplines involved in designing an aircraft, on the definition of design variables and their ranges, of constraints and of an optimization method. After the optimization is performed not much information is obtained from the results regarding to how and why the final configuration was the best.

Another approach to the studies was performing a sensitivity or parametric analysis, in which some parameters were selected and varied one by one. Their effect on the overall aircraft was assessed and so it was possible to have a better understanding of what makes the SBW configuration successful and what could make it unfeasible.

While MDO captures the synergistic features of the SBW, its results are dependent on the accuracy of the models. Performing a parametric analysis provides better understanding of the SBW, and helps better choose the design variables, their ranges and constraints for future MDO studies.

## 2. METHODOLOGY

Drag is a direct measure of aircraft efficiency, since it influences fuel consumption and emissions. The objective is to perform a parametric drag analysis of the SBW aircraft for regional aviation, while comparing it to a baseline conventional aircraft. For simplification it is assumed that: both aircraft present the same mission, wing reference area, fuselage, landing gear, engines and tails, but their wing geometry is different. Hence, comparisons are made only for a conventional wing against a wing plus strut geometry. The wing reference area is kept constant to simplify the analyses and the comparisons, since it is assumed that both aircraft present the same mission and total weight.

### 2.1 Parameters

The analyzed parameters were selected in an attempt to define the wing plus strut main geometric characteristics, as can be seen in Fig. 1. High level parameters were chosen over low level ones, meaning that aspect ratio is analyzed instead of wing span. This makes the analyses, understanding and extrapolation of the results to other aircraft easier, since it is a non-dimensional parameter.

The front view of the wing plus strut geometry can be seen in Fig. 1 (a), where the represented parameters are engine spanwise position  $e_p$ , the wing span  $b_w$ , the spanwise position of the wing and strut intersection  $b_s$ , the strut offset length  $L$ , the wing thickness at intersection with the strut  $t_w$ , the strut thickness at the intersection with the wing  $t_{s1}$ , the strut thickness at the intersection with the fuselage  $t_{s2}$ , the intersection angle between strut and wing  $\phi_1$ , and the intersection angle between strut and fuselage  $\phi_2$ .

The cross-sectional side view of the same geometry can be seen in Fig. 1 (b). The represented parameters in this view are the wing average thickness  $t_w$ , and the average strut thickness  $t_s$ .

The top view of the wing plus strut geometry can be seen in Fig. 1 (c), where the represented parameters are the wing quarter-chord sweep angle  $A_w$ , the root and tip chords of the wing  $c_r$  and  $c_t$ , the strut quarter-chord sweep angle  $A_s$ , and the root and tip chords of the strut  $c_r$  and  $c_t$ .

The airfoil design is assessed through technology factors. There is a technology factor  $TF$  for quantifying if the airfoil was designed to provide an extended region of laminar flow varying from 0 to 1. A low  $TF$  value implies that the

flow over the airfoil is mostly turbulent, whereas a high  $TF$  value implies that the flow over the airfoil is mostly laminar. A second technology factor called Korn factor  $\kappa_A$ , varying from 0.87 to 0.95, assesses if the airfoil was designed for transonic performance. A low  $\kappa_A$  implies that the airfoil was designed for subsonic flight, whereas a high  $\kappa_A$  implies that the airfoil is supercritical and designed for high transonic flight.

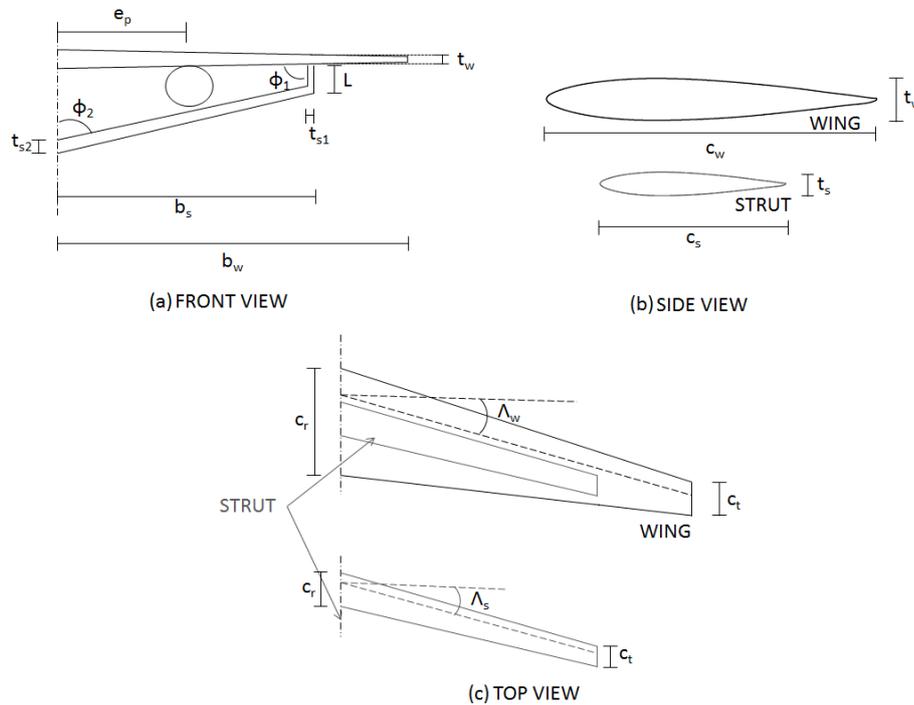


Figure 1. (a) Front (b) Side (c) Top view of the wing and strut geometry

A standard wing based on common regional aircraft is defined as a baseline, as can be seen in Tab. 1, where  $S$  represents area, the subscript  $w$  represents wing,  $AR$  is aspect ratio,  $\lambda$  is the taper ratio,  $r_n$  is the nacelle radius and  $d$  is the fuselage diameter.

Table 1. Wing baseline parameters

Parameter	Baseline Value
$S_w$	95 m <sup>2</sup>
$AR_w$	8.3
$A_w$	23°
$\lambda_w$	0.31
$TF$	0
$\kappa_A$	0.9
$c_b$	0.5
$e_p$	0.5
$(t/c)_w \text{ avg}$	9%
$r_n$	1 m
$d$	3.5 m

A standard strut was obtained based on the literature review (Tétrault, 2000), (Duggirala, et al., 2009) and (Seber, et al., 2011), and is defined in Tab. 2, where the subscript  $s$  represents strut, and  $\eta$  is the dimensionless spanwise position of the wing and strut intersection.

The flight condition analyzed was cruise at Mach 0.8, 35000 ft, with a Reynolds number of  $2.3 \times 10^7$ .

## 2.2 Drag breakdown

A typical drag breakdown was conducted according to Gur, et al. (2009), as can be seen in Fig. 2. The wing drag is divided in parasite and induced parts. The parasite drag was further divided in friction, form, interference and wave drags.

Table 2. Standard strut parameters

Parameter	Standard Value
$A_s$	23°
$\phi$	90°
$\lambda_s$	1
$TF$	0
$\kappa_A$	0.9
$\eta$	0.7
$R$	0.25
$(t/c)_{s\ avg}$	7%
$(t/c)_w$ and $(t/c)_s$ at junction	7%
$(t/c)_s$ at fuselage junction	7%
$L$	1 m

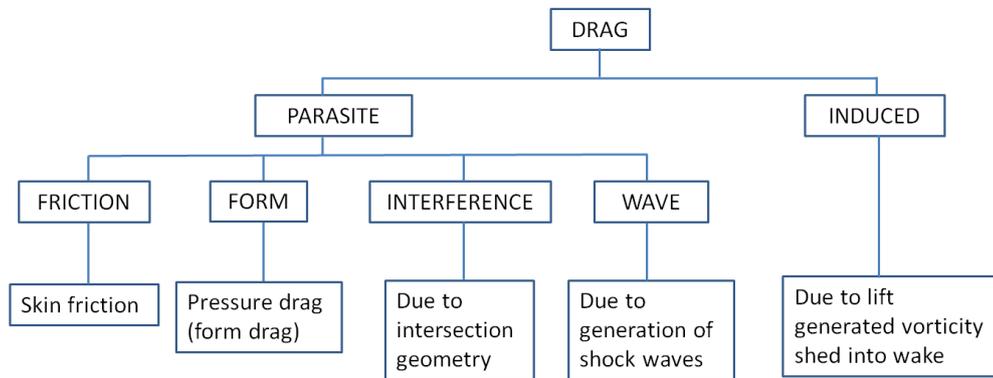


Figure 2. Typical drag breakdown

The friction and form drag coefficient is obtained, as presented by Gur, et al. (2009) according to Eq. (1),

$$C_D = C_F \times FF \times \frac{S_{wet}}{S_{ref}} \quad (1)$$

where  $C_F$  is the skin friction coefficient for a flat plate,  $FF$  is the form factor,  $S_{wet}$  is the wetted area and  $S_{ref}$  is the wing reference area. The skin friction coefficient is obtained using standard flat plate skin friction formulas for laminar (Eq. (2)) and turbulent (Eq. (3)) flow separately. To account for a combination of laminar and turbulent flow over the wing, Schlichting's composition formula (Eq. (4)) is used.

$$C_{F_{lam}} = 2 \times C_f = 2 \times \frac{0.664 \times \sqrt{C^*}}{\sqrt{Re_x}} \quad (2)$$

$$\frac{0.242}{\sqrt{C_{F_{turb}}}} = \log(Re_x \times C_{F_{turb}}) \quad (3)$$

$$C_F = C_{F_{turb}}(Re_L) - \left(\frac{x_c}{L}\right) \times [C_{F_{turb}}(Re_c) - C_{F_{lam}}(Re_c)] \quad (4)$$

The form factors were obtained through empirical formulas by Torenbeek (1982), such as Eq. (5).

$$FF = 1 + 2.7 \frac{t}{c} + 100 \left(\frac{t}{c}\right)^4 \quad (5)$$

The wave drag was obtained using Korn's equation extended with simple sweep theory (Mason, 1990) and Lock's fourth power law (Hilton, 1951). For Mach numbers above the critical Mach  $M_{cr}$ , the wave drag coefficient is obtained through Eq. (6).

$$C_{d_w} = 20 \times (M - M_{cr})^4 \quad (6)$$

The critical Mach number  $M_{cr}$  is obtained when Eq. (7) is satisfied, where the drag divergence Mach number  $M_{DD}$  is obtained through Eq. (8).

$$M_{cr} = M_{DD} - \sqrt[3]{\frac{0.1}{80}} \quad (7)$$

$$M_{DD} \times \cos \Lambda_{0.5} + \frac{C_l}{10 \times \cos^2 \Lambda_{0.5}} + \frac{t/c}{\cos \Lambda_{0.5}} = \kappa_A \quad (8)$$

The interference drag due to the wing-strut and the wing-fuselage intersections, in transonic flow, is mainly due to separated flow regions and unwanted shock waves. It is crucial that the interference drag caused by the strut is small compared to other drag sources, so that the SBW aircraft concept is viable. The model used to assess this drag consists of CFD-based results for two streamlined intersecting sections and of a streamlined section intersecting a wall obtained from Duggirala, et al. (2009) and Tétrault (2000), respectively, and empirical models considering several characteristics obtained by Hoerner (1965) for low Mach numbers. Duggirala, et al. (2009) and Tétrault's (2000) models, seen in Tab. 3 and Tab. 4, respectively, can only be applied for wing and strut thicknesses between 5% and 7.5%. For higher thicknesses Hoerner's (1965) data, seen in Tab. 5, is applied.

Table 3. Interference drag coefficients obtained by Tétrault (2000)

NACA Airfoil	$\phi$	$Re_c = 5.3 \times 10^6$	$Re_c = 10.6 \times 10^6$
64A005	90°	0.0006	0.0006
	60°	0.0038	0.0028
	30°	0.0238	0.0207
64A007.5	90°	-0.0010	-0.0011
	60°	0.0080	0.0067
	30°	0.0547	0.0487

Table 4. Interference drag coefficients obtained by Duggirala, et al. (2009)

NACA	$\phi$	Mach = 0.8	Mach = 0.85
64A005	45°	0.010208	0.031156
	60°	0.007891	0.021097
	75°	0.005871	0.016447
	90°	0.005356	0.028961
64A007.5	45°	0.02667	0.12821
	60°	0.01810	0.10464
	75°	0.01703	0.099736
	90°	0.01984	0.10530

Table 5. Interference drag coefficient equations obtained from data by Hoerner (1965), as applied by Grasmeyer (1998)

Intersection	$C_D$
Wing intersecting flat wall at 90°	$(0.8(t/c)^3 - 0.0003)c^2/S_{ref}$
Two intersecting streamlined sections at 90°	$(17(t/c)^4 - 0.05(t/c)^2)c^2/S_{ref}$
Due to lift coefficient	$(0.1C_L^2)c^2/S_{ref}$
Due to sweep of the junction	$(-0.000018\alpha^2 + 0.00009\alpha)c^2/S_{ref}$
Due to inclination (dihedral) of the junction	$(0.000006\beta^2 + 0.0015\beta)c^2/S_{ref}$

The induced drag was obtained using the Vortex Lattice Method (VLM), as implemented by Tomas Melin (2000) in the Matlab program called “Tornado”, with Prandtl-Glauert transformations for consideration of compressibility effects. Since difficulties in the solution convergence, singularities and discontinuities were observed for the SBW geometry, a mesh modeling rule was adopted. The intersection between wing and strut should be so that no vortex line crosses any control point and so that the bound vortices of the wing and of the strut coincide, as represented in Fig. 3. A mesh convergence of the SBW geometry was carried out, where  $C_{Di}$  and the Oswald efficiency number  $e$  values were compared, as can be seen in Fig. 4 and Fig. 5.

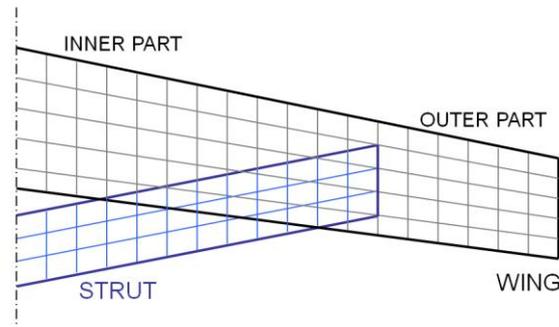


Figure 3. Top view of a wing plus strut half-geometry discretized in panels

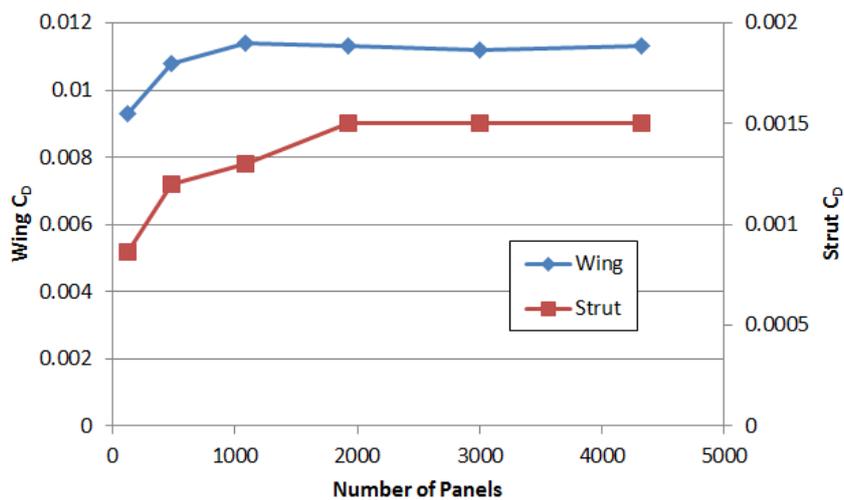


Figure 4. Mesh convergence of wing plus strut geometry according to induced drag value

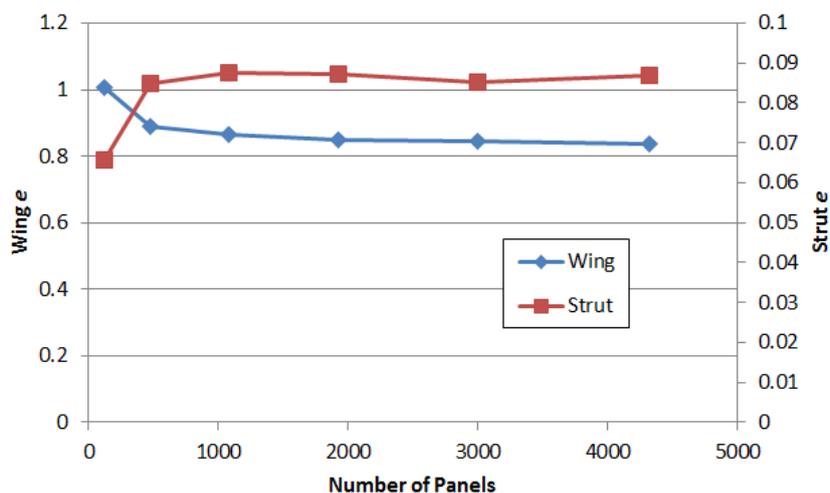


Figure 5. Mesh convergence of wing plus strut geometry according to Oswald efficiency number

As can be seen in Fig. 4, convergence was observed for a mesh of 1920 panels. This mesh presents 20 divisions along the chord of the wing, 8 divisions along the chord of the strut, 20 divisions along the span of the inner part of the wing and along the span of the strut, and 20 divisions along the span of the outer part of the wing, as can be seen in Fig. 6.

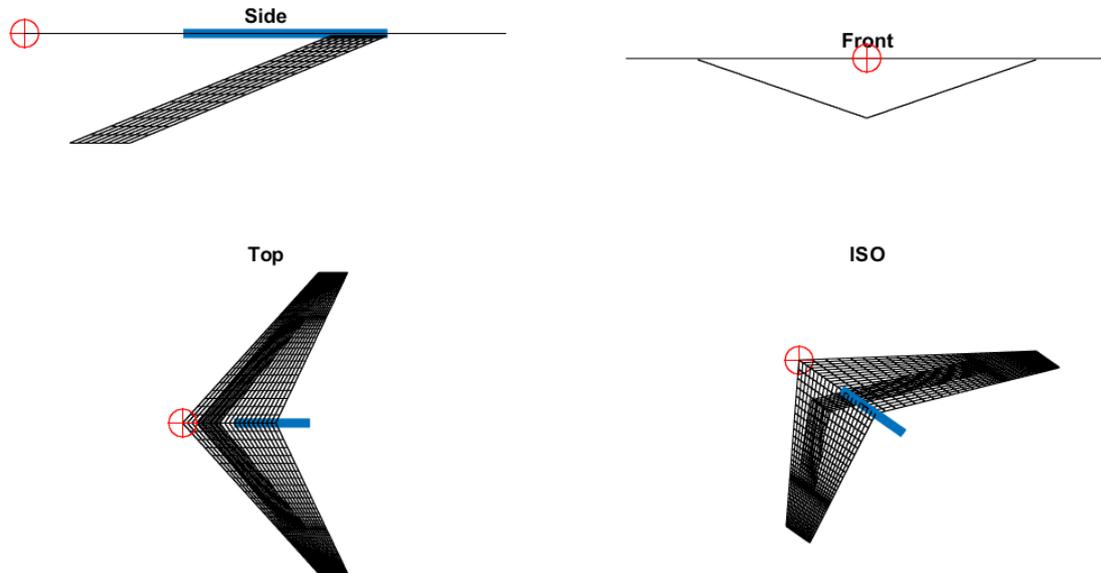


Figure 6. Wing plus strut mesh with 1920 panels

### 2.3 Results

To assess the impact of each type of drag on the total drag of the SBW geometry, the drag breakdowns of the baseline wing and of the wing plus strut geometry were analyzed, as can be seen in Fig. 7. Four drag breakdowns are compared: the first, subtitled *Wing*, consists of the baseline wing geometry; the second, *Wing + strut 1*, consists of the wing plus standard strut geometry with the intersection angle between wing and strut of  $45^\circ$  and intersection angle between strut and fuselage of  $30^\circ$ ; the third, *Wing + strut 2*, consists of the wing plus standard strut with intersection angles of  $90^\circ$ ; and the fourth, *Wing + strut 3*, consists of a wing of aspect ratio 14, the standard strut and intersection angles of  $90^\circ$ .

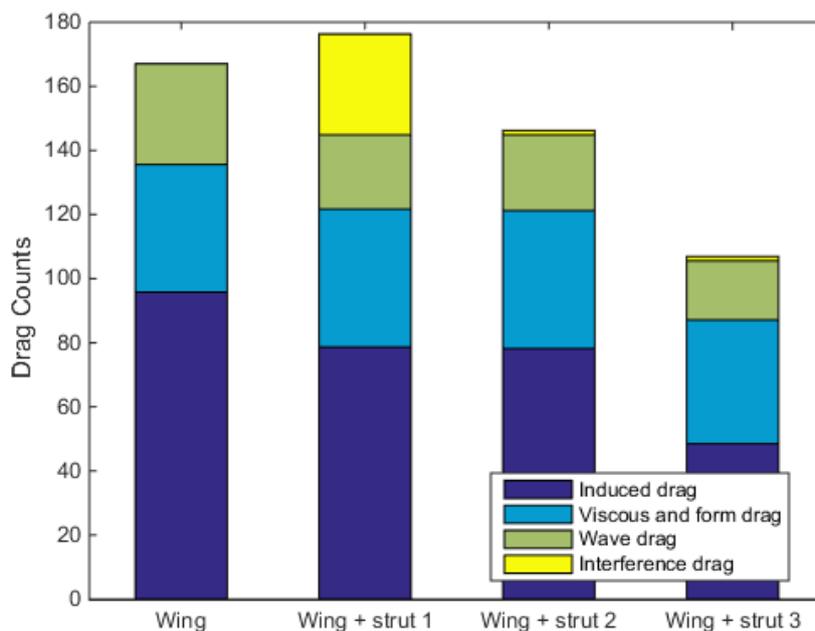


Figure 7. Drag breakdown comparison between the wing only and the wing plus strut for  $CL = 0.46$

It can be seen that *Wing + strut 2* presents a lower total drag than *Wing*, for an equivalent flight condition. This is due to the effect of the strut unloading the wing, and consequently reducing the induced and wave drags.

It is important that the SBW configuration presents intersections with low interference drag values, since when small intersection angles are used the total drag of the SBW geometry is higher than that of the wing only.

As can be seen in Fig. 7, the *Wing* presents 167 drag counts, whereas the *Wing + strut 1* presents 176 drag counts and the *Wing + strut 2* presents 146 drag counts. For the *Wing + strut 2* a decrease of around 12% in drag is observed when compared to the wing only. Although there is an increase in friction, form and interference drag when adding the strut, there is a decrease in the wave and induced drag, and this decrease is higher. The increase in friction, form and interference drag is due to the addition of the strut, another streamlined body, to the geometry. The decrease in wave and induced drag is mainly due to the unloading of the wing, as can be seen in Fig. 8. For maintaining the same total  $C_L$  some of the load is carried by the strut on the wing plus strut geometry. This accounts for less load being carried by the wing, hence lower induced and wave drag. In addition, the wing loading on the wing tip was smaller when compared to that of the baseline wing, reducing induced drag. The remaining load, carried by the strut, accounts for low induced drag because the strut has a higher aspect ratio than the wing and presents the equivalent to wing tip devices provided by the intersection with the wing, and low wave drag because  $C_l$  values are lower. The sum of the induced drags of the wing and the strut is therefore lower than the induced drag obtained by the wing only. This analysis indicates that the strut could be more loaded than the wing, since it presents a higher aspect ratio.

As for *Wing + strut 3*, if a SBW geometry with a wing aspect ratio of 14 is considered, a total drag of 107 counts is obtained. This is a decrease of almost 36% when compared to the wing only geometry, and serves as an indication of the potentials of the SBW configuration. However, it has to be noted that no structural and weight analysis was performed for obtaining these results. A performance analysis regarding the aircraft mission should provide the actual results in fuel consumption.

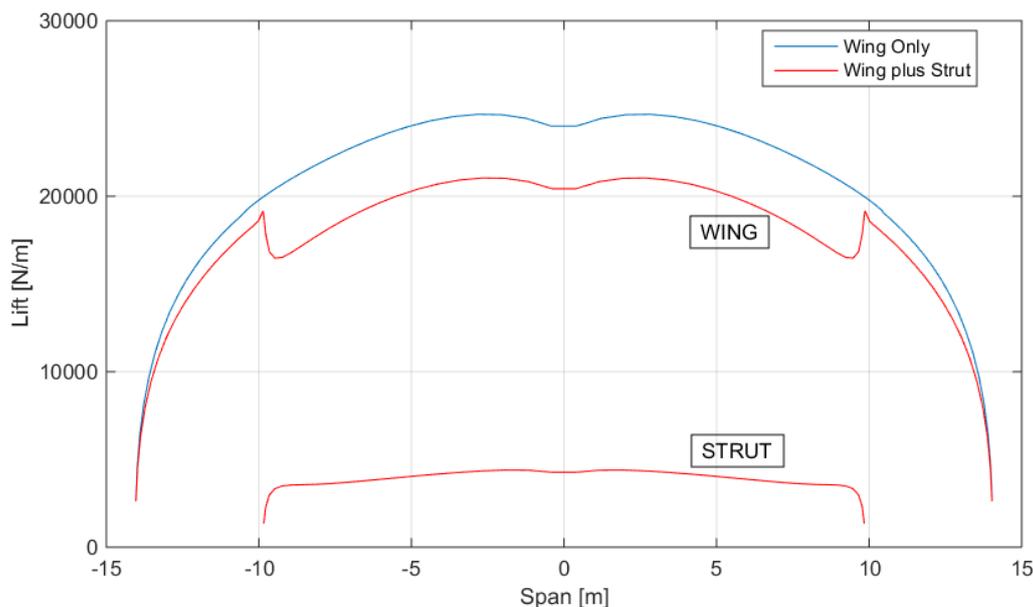


Figure 8. Loads distribution for wing only and for wing plus strut geometry

Even though sudden changes in lift are observed on the wing on the intersection region, this did not increase the induced drag excessively according to the results obtained. Sudden changes in lift cause vortices, as represented in Fig. 9 in grey. There are changes in lift at the strut tip, also causing vortices, represented in blue in Fig. 9. These two vortices present opposite rotatory directions and might be canceling each other out, or at least reducing their effect on the total induced drag.

A parametric analysis of the total drag of the SBW configuration was performed, as can be seen in Fig. 10. As expected, it is possible to see that the wing aspect ratio presents great influence over the drag values, where the decrease in drag is due to the decrease in induced drag. The wing sweep presents less influence, and the decrease observed is mainly due to the reduction in wave drag. The wing thickness presented itself to be very critical, with larger thicknesses incurring in an expressive increase in wave and form drag. This effect is also observed, with less intensity, on the strut thickness.

As for the technology factor, it is possible to see that the Korn factor, regarding supercritical airfoil technology, presented greater influence on the overall drag values than the laminar technology factor.

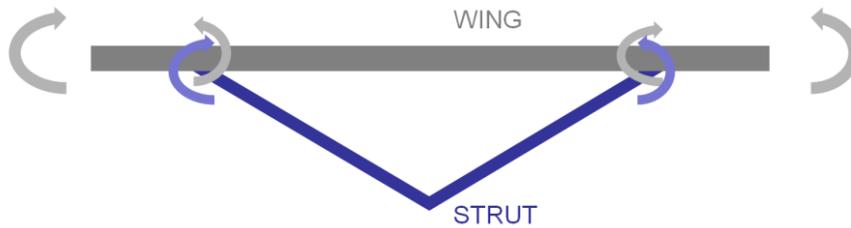


Figure 9. Wing, in grey, and strut, in blue, with vortices

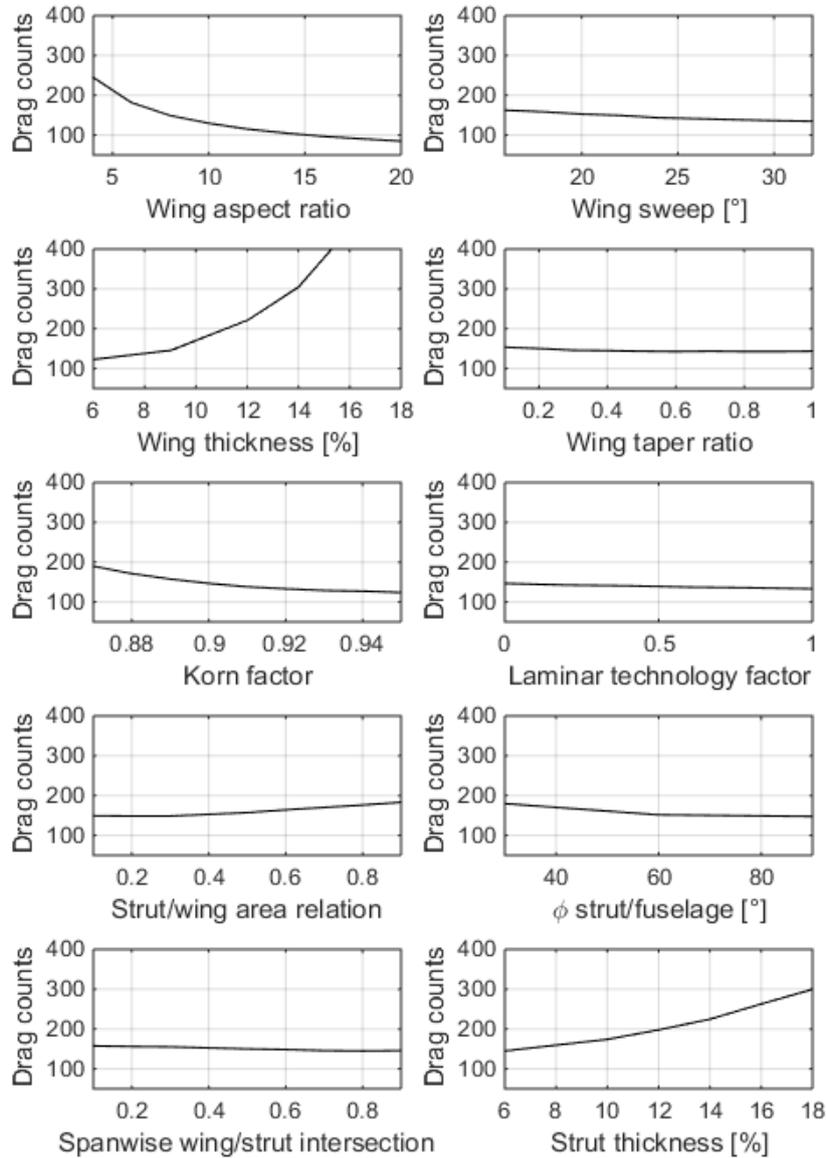


Figure 10. Parametric drag analysis

Increasing the strut area causes a drag increase, mainly due to friction drag, whereas decreasing the intersection angles between the strut and other parts causes shock waves and flow separation, increasing interference drag. Changes in the spanwise wing and strut intersection do not present expressive changes in drag values.

### 3. CONCLUSION

It is possible to conclude from this parametric analysis that, for a SBW configuration: it is interesting to keep wing and strut thicknesses small, as well as employing supercritical airfoils, so to not present high values of drag due to

shock waves; a high aspect ratio wing would benefit this configuration even further, as expected; a small strut area is interesting because it would minimize the increase in drag due to friction; and, as observed, sweep angle values do not influence the total drag as much as other factors.

Furthermore, it was observed that if perpendicular intersections are considered, the SBW configuration can present 12% less drag than the conventional configuration considering the same wing geometry. Considering a wing aspect ratio of 14 on the SBW configuration, a decrease of drag in the order of 36% can be obtained. It has to be noted that, for an assessment of improvements in fuel consumption a performance analysis, considering the aircraft mission, drag and weight, should be performed.

#### 4. ACKNOWLEDGEMENTS

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