PASSIVE, ACTIVE, AND ADAPTATIVE SYSTEMS FOR WING VORTEX DRAG REDUCTION

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Abstract

A group of experimental studies were conducted to investigate the effects of different wing tip devices and systems on the reduction of induced drag. Fixed or passive devices, active systems as well as adaptive systems were analyzed in wind tunnel tests. The experiments were conducted in three stages: 1) an analysis of the effect of delta tip, winglet, and "Hoerner" devices, concerning the aerodynamic characteristics of an agricultural airplane wing; 2) an analysis of the effect of wing tip blowing on vortex drag through a novel system composed of three vectorable Coanda jets; and 3) an analysis of the aerodynamic characteristics of adaptive multi-winglets. Results showed that it is possible to achieve optimum aerodynamic performance for each wing tip system when the mission is precisely defined.

1 Introduction

The vortices produced at the wing-tip are the inevitable products of the presence of lift, that is to say, they may be considered to be side effect due to the force that supports the aircraft in the air. These vortices are responsible for the appearance of induced drag. In cruise conditions the induced drag may be responsible for approximately 30% of the entire aircraft drag and close to 50% in high lift conditions [1]. With the intention of reducing the induced drag, an expansive investigation was made of the methods that have been used to produce favourable effects in the flow existent over the wing tip, including devices that reduce the induced drag. Modifications of the wing tip can either move the vortices away in relation to the aircraft longitudinal axis or reduce their intensity [2]. Some of these devices such as winglets [3], tip-sails [4], [5], [6], [7] and multi-winglets [8] take advantage of the spiralling airflow in this region to create an additional traction, and reducing the induced drag. Drawings of these previous devices are shown in Fig. 1.

Whitcomb [3] showed that winglets could increase wing efficiency by 9% and reduce induced drag by 20%. Other devices break up the vortices into several parts, each with less intensity facilitating dispersion, which is important, for instance, for the decrease of the interval time between takeoff and landings in large airports [9]. Kravchenco [2] tested and compared different shapes of wing tips: winglets and tip-sails. The winglets presented higher aerodynamics benefits up to Mach 1.0, however they also presented structural problems for the aircraft due to the increase in bending moment at the wing root.

Tip-sails, at low lift coefficient, provided the same benefits; nevertheless, the bending moment at the wing root was less. Research with agricultural aircraft has also been made comparing wing-tip devices [10]. For this category of aircraft, besides both aerodynamic and structural advantages, the influence of the vortices created during the mission of the aircraft is an added parameter in the analysis.

Winglets have been used to improve sailplane performance. Smith [8] mentions the development work on winglets for sailplanes tested in a wind tunnel with scale models.

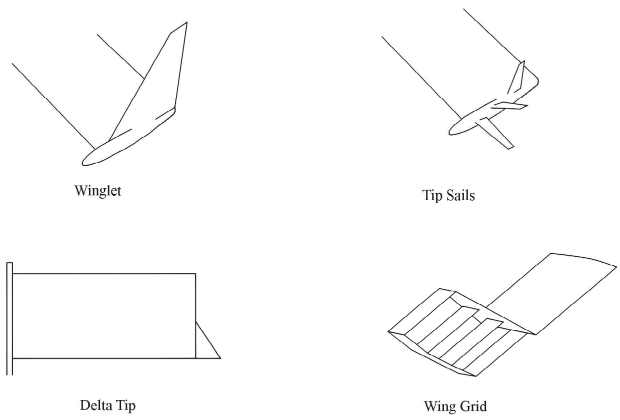

Fig. 1 Wing tip devices

It was mentioned that winglets with symmetric airfoils are considered better for general aviation use; yet, they are less efficient when applied to tapered wings. Projects of new airfoils for winglets used on sailplanes have been developed and tested. Due to the low Reynolds number flow at the winglet; a spanwise variation of the airfoil is of fundamental importance for optimizing winglet performance. Maughmer [11] presented a methodology for the design of winglet airfoils.

Spillman et al. [4], [5], [6], [7], realized a series of studies of small aerodynamic devices named tip-sails. These devices took advantage of the direction of the flow existent over the wing tips to create a thrust force, and they also present a reduction in the vortex intensity. The conclusion is, once a particular flight condition has been chosen, the geometry of the tip-sail must present twist and taper ratio. The airfoil must be highly curved at the root and symmetric at the tip. This is due to the behavior of the flow over the wing tips where flow inclination angle decreases with radial distance from the wing tip. Spillman et al. [4], [5], [6], [7] also investigated the use of tip-sails installed on the tip-tank of a Paris MS 760 Trainer Aircraft [4], [5]. Better results were found using 3 tip-sails. The flight tests confirmed the results achieved in wind tunnel tests such as take off distance and fuel consumption [5]. Also flight tests of a Cessna Centurion [6] and a Piper Pawnee 235 [4], [7] were performed using tip-sails. All of these tests presented benefits to the aircraft performance. Tip-sails are the only device that can reduce fuel consumption as well as present structural advantages for the wings.

On the other hand, active systems can be optimized for each maneuver requirement as their effect can be changed and also switched off when necessary. A large number of studies [12], [13], [14], [15] have been carried-out in order to show the potential benefits of wing tip blowing as an active vortex attenuating system. These tests usually involved large jet momentum coefficients and the jet sizes were a large fraction of the wingtip chord. Also, the required jet mass-flow rates and momentum coefficients were large. In most cases, the jets were exhausted in the plane of the wing and normal to the free-stream direction. Recently, Simpson [16] introduced a different type of jet system, which was based on the Coanda effect. This type of jet is able to direct the mass flow against the vortex and the mass flow rate is small as is the size compared with the tip chord. In this work, the proposed system consists of three independent Coanda jets, which can be vectored in different directions (see Fig. 2.) in a tentative to oppose mass flow against the vortex flow in a similar manner to that of Spillman [4] with his tip sails.

Multiple slotted wings has been studied in order to explain the aerodynamic performance of inland soaring birds, notably by Tucer [23]. The potential benefit on using similar configuration of aircraft wings has been analyzed by Cerï£¡-Muï£¡z, and Catalano [22] and Smith et al [8].

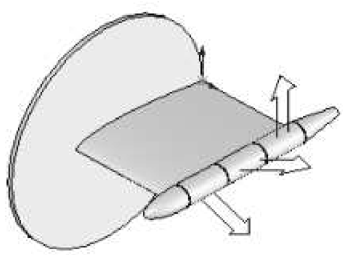

Fig. 2 Three wing tip "coanda" jets

Results shown that induced drag can be reduced in various flight regimes by changing both twist and cant angles. The feasibility of such adaptive device is highly dependent on a smart system that can couple with the amount of information and set the best configuration for each flight regime.

The aim of this paper is to analyze the aerodynamic performance of three types of wing tip systems: a passive or fixed, an active system by spanwise blowing at the wing tip and an adaptive system composed of three wing lets which cant and incidence angle can be changed.

2 Wing tip for agricultural airplane

The importance of wing tip treatment in agricultural aircraft is a key factor for the increase of the spray strip size as well as diminishing the amount of evaporated droplets caused by the tip vortex. This application of a passive wing tip device was chosen because of the unique flight conditions encountered in an aerial spraying mission: a) The aircraft operates all the time in a high wing load condition with $C_L > 1.0$ and induced drag should be high, b) A highly loaded wing also produces a strong downwash which is very important for targeting the crops with the spray, c) Ground effect is also high due to the flight path being very near the ground.

The best tip device for this application should be a solution of compromise between induced drag intensity, vortex core position to avoid ground interaction and, enough downwash. To find this solution, wind tunnel tests were made in order to study the influence on aerodynamic characteristics and vortex position, for a Brazilian agricultural aircraft, using the following types of wing tips: delta tip, winglet and down curved. The down curved tip was included in the search because it was originally used in the production aircraft. The delta tip [17] is the most simple and easy to repair, an important issue as the environment during the spraying is very tough and demanding. The winglet is probably more efficient in reducing induced drag and, its optimization in coping with the previously mentioned requirements should be studied. The wing tip device increases lift at the tip region with a consequent increase of bending moment at the wing root. More bending moment leads to more structural weight and less payload; consequently the increase of the bending moment should be taken in account in the analysis of the apparent vantages of the wing tip devices.

2.1 Experimental Configuration

The tests were made at the University of Sï£¡ Paulo, Aircraft Laboratory, in an open circuit wind tunnel which has a hexagonal test section with a cross section area of $0.526m^2$ and $1.63m$ length. The wing profile used was a NACA 23015 with drooping leading edge, which increases the maximum lift of the original airfoil. The wing model used a rectangular plan form and it has $0.138m$ chord, $0.389m$ half span and no geometric twist. The aspect ratio (AR) of the basic wing was 5.63. Fig. 3 shows the tested models. The winglet, which was canted outward 20°, was tested at 5° incidence angle; and was constructed with a NACA 23015 airfoil section, from wood, with a total winglet area of 12% of the wing area. As showed in the winglet planform was tapered with a 15° leading edge sweep angle; its root chord and span had the same geometric value: 66.6% of the wing chord. It should be noted that the winglet test was exploratory and limited in scope; no attempt was made to optimize winglet geometry for maximum aerial application benefits. The delta tip was made from $1mm$ thick aluminum plate and had a leading edge sweep angle of 70°. This tip had 0.91% of the wing area and the root chord corresponded to 37.7% of the wing chord. The leading edge of the delta tip was sharp to enforce flow separation. Both configurations were positioned near the wing trailing edge. The downward curved tip was made from styrofoam and had 8,6% of the wing area. This tip device equipped the second generation of Brazilian agricultural aircraft (from EMB- 201A to EMB-202, all called Ipanema). The aerodynamic forces were measured with a strain gauge balance. All the results were corrected for wall interference. [18]. The two-component balance used is of the strain gauge type and has a measurement accuracy of ± 0.7 per cent at maximum loading. Giving accuracies for lift and drag of ± 1.0 and $\pm 0.19N$, respectively. Tests were conducted at a freestream velocity of $28m/s$. The geometric angle of attack, with reference to the tunnel axis, was varied from 0 to 15 degrees. Wing Reynolds number was $2.7x10^5$, based on chord length. The wing had a roughness strip at 5% of the chord on the upper and lower surface along the entire wing span in order to fix boundary-layer transition. Wing root bending moments measurement were also made, to verify any structural overloading or damage, using the same strain-gage balance.

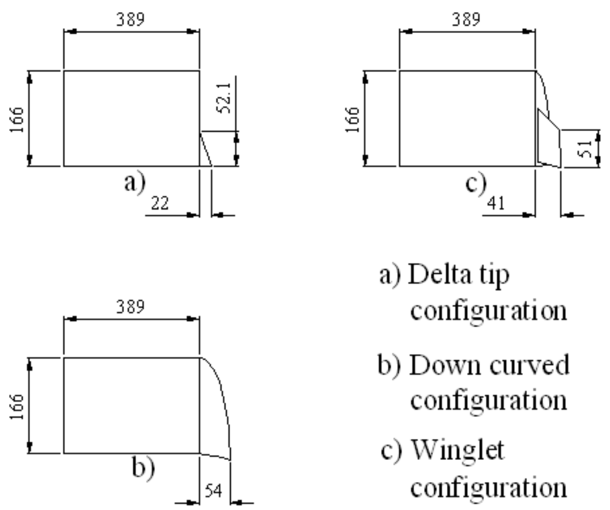

Fig. 3 Wing tip configurations

2.2 Results and Discussion

The Fig. 4. presents the lift curves and shows an increase in lift coefficient for all tip configurations compared to the basic wing. Fig. 5. shows drag polar curves.

To quantify the induced drag performance in the most useful lift range, the drag polar may be approximated using equation 1.

$$C_D = C_{Dmin} + C_L{}^2/\pi \cdot AR \cdot e \qquad (1)$$

where C_D is the drag coefficient, C_{Dmin} is the minimum drag coefficient, AR is the wing aspect ratio, and e is the Oswald efficiency factor.

The shape of the tip, including the sharpness of the edge and the trailing edge of the wing tip are all important in directing the vortex as far outward as possible, thus increasing the span efficiency.

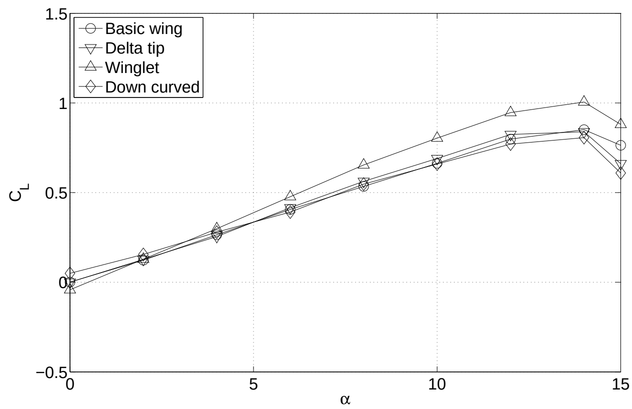

Fig. 4 Lift coefficient versus incidence angle

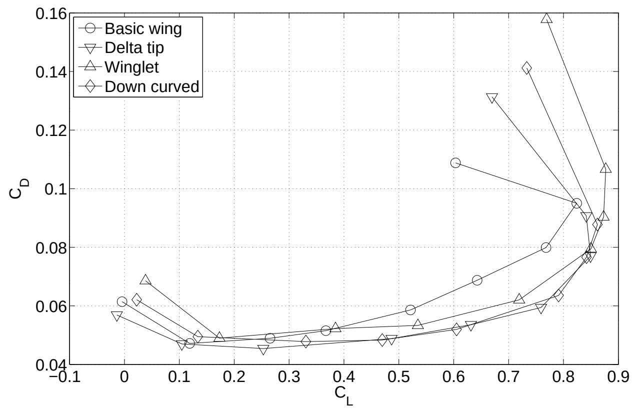

Fig. 5 Drag polar curves

The constant e incorporates both vortex and profile drag, which are difficult to separate as both vary with $C_L{}^2$. To calculate values of the Oswald efficiency for each of the wing tips tested, the relationship used was Eq. 2 [19].

$$e = 57.3\frac{dC_L}{d\alpha_\infty} \cdot [(\varphi - 1)\pi \cdot AR] \qquad (2)$$

were is the lift curve slope ratio. Improvements in factor e directly affect the performance of the airplane, especially at high lift conditions. In Fig. 6., at small angles of attack $\alpha < 6^\circ$, the delta tip device shows less drag than the other wing-tip configurations; at higher incidences, the down curved tip presents smaller drag coefficients. In Fig. 5. drag polar shows the same pattern presented in Fig. 6., at lift coefficients of less than 0.4 for delta tip and higher for down curved tip. Winglet presented higher drag than the others tip devices, at lift coefficients smaller than 0.4; at $CL's$ from 0.4 to 0.8 the winglet drag is equal to the delta tip values.

At much higher lift coefficients, the winglet has a small advantage over the down curved tip. It should be noted that the addition of the tested tips increased the geometric aspect ratio of the basic wing and this was taken into consideration for the Oswald efficiency factor calculations. The aerodynamic efficiency is presented in Fig. 7. At angles of attack less than 7°, the winglet shows a better L/D ratio; after this incidence, the down curved tip presents better aerodynamic efficiency.

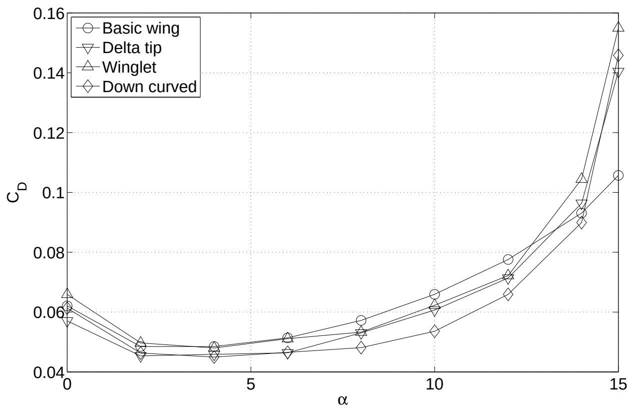

Fig. 6 Drag coefficient versus incidence angle

The improvements in wing performance with the new wing tips can be related to the increase in aspect ratio, improvements in span efficiencies and changes in the zero lift-drag coefficients. Fig. 8 shows rate of climb.

All aerodynamic benefits had their importance reduced, if structural damages are caused on the wing by the addition of the wing tips, then structural reinforcements are needed, increasing the wing weight and reducing fuel capacity and payload. Fig.9 presents the parameter $\Delta Ef/\Delta Mb$. This parameter, called the aerodynamic structural efficiency factor (ASEF) is used to measure the relation between the beneficial increment on wing aerodynamic efficiency to the detrimental increment on wing root bending moment, caused by the addition of the wing tips.

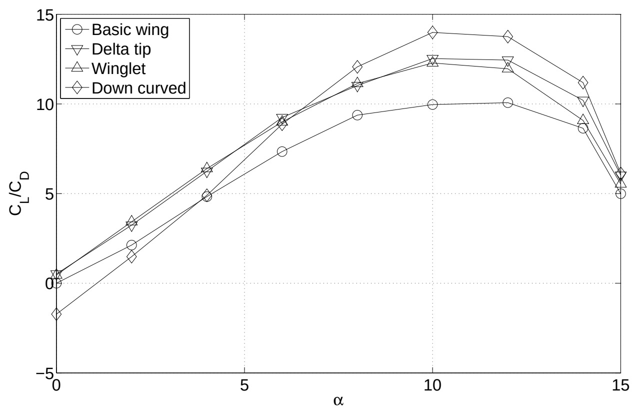

Fig. 7 Lift to drag curves

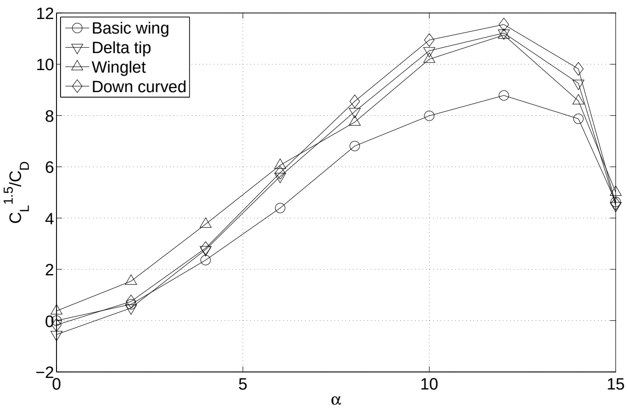

Fig. 8 Climb factor

The variation of wing efficiency and its root bending moment is compared with the basic wing at each incidence angle; then the basic wing has its parameter equal to the unity at all angles of attack range. It can be noted, in Fig. 9, that only the winglet presents ASEF less than the unit for angles of attack higher than 8°.

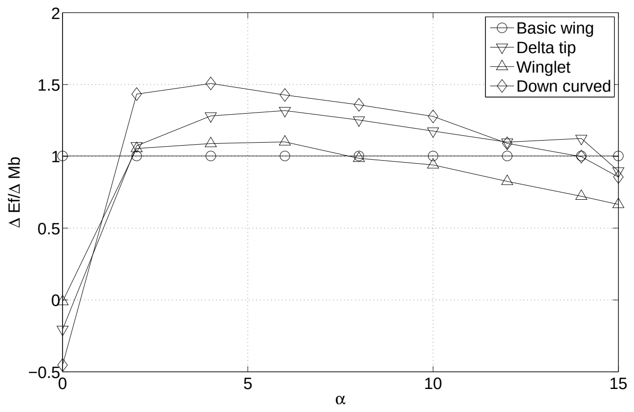

Fig. 9 Effect of win tip devices on rate climb factor

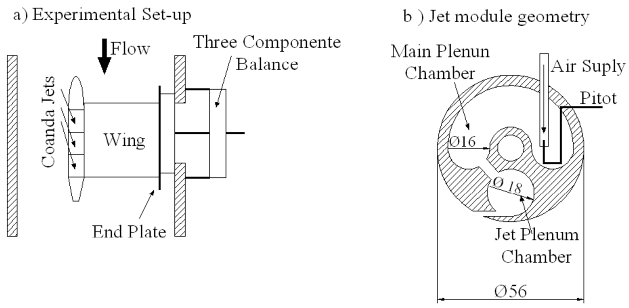

Fig. 10 Experimental set-up and jet module geometry

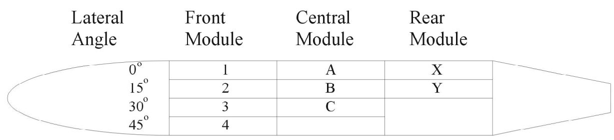

Fig. 11 Tip jet modules nomenclature

3 Wing tip blowing on vortex

Experimental work was performed for a large combination of jet flow lateral angles and positions of the tip chord for incidence angles from -4 to 22 degrees always comparing with that of the blowing off case.

3.1 Experimental Configuration

The experimental model was a semi-span wing of $0.29m$ with a $0.25m$ chord. The wing profile was a NACA $65_3 18$ and the model was attached to a horizontal three-component balance as is shown in Fig. 6. The three Coanda jet modules were fixed to a cylindrical "tip tank" for the convenience of providing enough space for the air manifolds and internal plenum chambers to assure as uniform a jet as possible. Each Coanda Jet module has an air supply manifold with mass flow controlled by a flow meter. Details of the jet dimensions and chambers are shown in Fig. 10.

Tests were conducted at the Institute of Aerospace Technology in an open circuit wind tunnel with a $0.6mx0.6m$ test section at an average Reynolds Number of $4x10^5$. Turbulence intensity was 0.5% at $30m/s$. All the results were corrected for wall interference.

Limited smoke flow visualization tests were performed with a small wing model in a smoke wind tunnel in order to pre-select the best jet configuration, avoiding in this way a large number of useless tests.

It was thus decided to test lateral angles in steps of 5° from 0o to 45° for the first module, 0° to 30° for the central module and 0° to 15° for the rear module.

The configuration nomenclature and reference positions are shown in Fig. 11. For example: tip blowing 1CY means that the first module is blowing at 0°, central module at 30° and rear module at 15°.

The three-component balance of strain gage type was used. Jet momentum coefficient C was calculated using the Eq.3

$$C_\mu = 2\frac{P_e}{q_\infty}\frac{S_j}{S_W} \qquad (3)$$

where P_e is the total pressure in the module plenum chamber, q_∞ the free stream dynamic pressure and S_j and S_W are the jet and wing area respectively.

3.2 Results and Discussion

Because of the large number of configurations tested, data reduction of the best results will be presented. The data presented always includes the blowing off case as a reference. As expected from previous work [12], [16] jets located at the rear of the chord tip are more effective in Lift enhancement as occurs with a winglet. This is probably due to the shift of the lift produced by the Coanda effect in the downstream direction when the interaction between jet and vortex increases at high incidences. Both configurations, 3A and CX, are the double jet configurations, whit presented best performance. Jet CX presents reasonably large Lift enhancement as can be seen in Fig. 12.

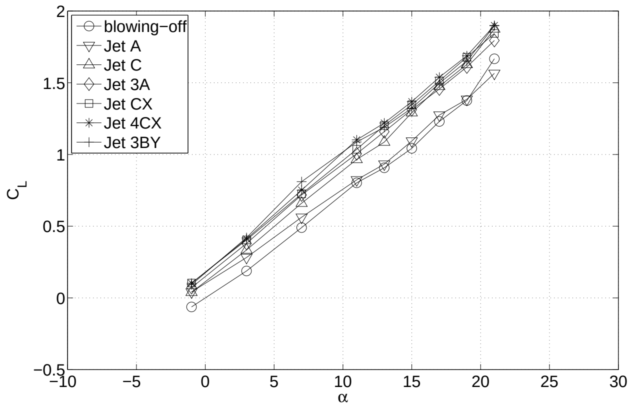

Fig. 12 Lift coefficient for the best configurations

At jet 3A the effect was still large but lift slope decreased. Drag results also shown in Fig. 14 are also very similar at low incidences but best overall performance is achieved with Jet CX for which induced drag reductions are larger. Therefore, Jet CX also shows the best aerodynamic performance enhancement as shown in Fig. 13.

The triple jet configurations selected are: 3CX and 3BY. Both Jet 3CX and 3BY show a slightly greater increase in Lift as shown in Fig. 12. This could be a result of an increase in effective aspect ratio but the weak shift of $CLx\alpha$ curve indicates that lift has increased by both the Coanda effect and then increase in effective aspect ratio with probably a greater contribution from the first. The Drag polar,as can be seen in Fig. 15, shows a large improvement for all jets especially at high incidences. The potential flexibility of operation of an active system as that proposed is shown in Fig. 16 and Fig. 17.

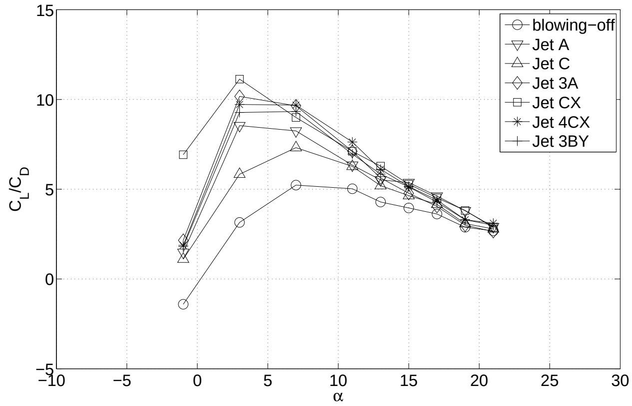

Fig. 13 Lift to drag curves

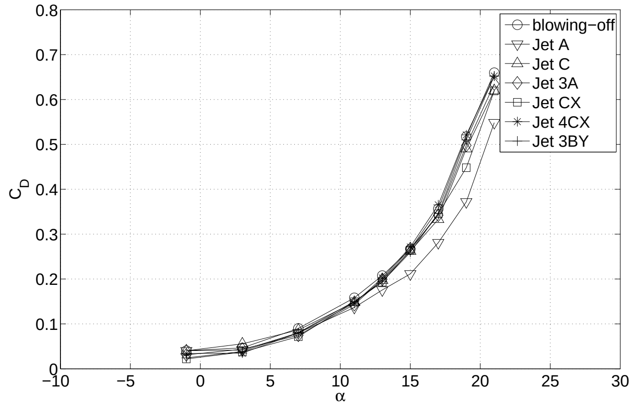

Fig. 14 Drag versus incidence angle

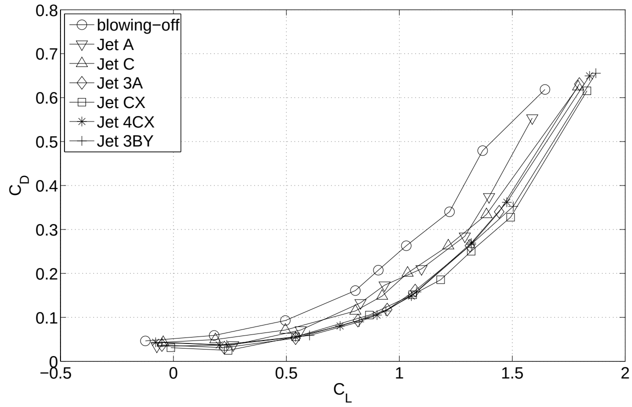

Fig. 15 Drag polar vurves

It is possible to change the positions of the jets from 3A or 3BY to CX in order to maintain best performance with reference to climb rate and maximum range.

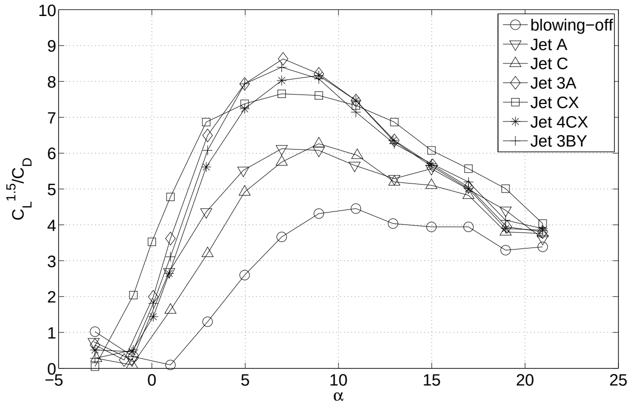

Fig. 16 Climb factor

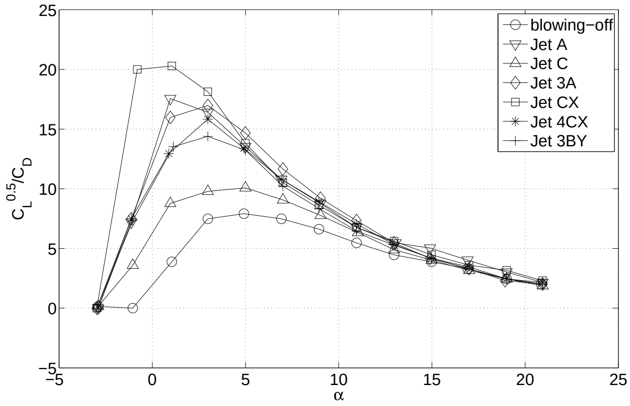

Fig. 17 Range factor

The lift enhancement due to the Coanda effect at the tip is a non-circulation born lift force justified by the fact the drag has not increased induced by the lift. Oswald factor has increased to values larger than that obtained in a similar manner with the winglets to an average value of 1.7 for all configurations tested.

4 Experimental Analysis of the aerodynamic characteristics of adaptative multi-winglets

The aim of this research is to study the potential use of adaptive multi-winglets for the reduction of induced drag through variations of winglet cant angles. The model tested is composed of a rectangular wing using a NACA 65_3-018 profile with three winglets called "tip-sails"', which are small wings without sweep

4.1 Experimental Configuration

The experimental model was a rectangular semi-span wing of 0.49m with a chord of 0.25m. For this study a tip tank with three vectorable cylindrical Coanda jets was developed [20]. The wing airfoil used was a NACA 65_3-018. Three winglets were added to three cylindrical modules at the tip-tank. The winglets have different airfoil sections along their span. At the root the airfoil is based on the Eppler 387 with 0.05m chord with a camber of approximated 20%. At the wing tip, the Eppler 387 airfoil was used again, but modified for a symmetric geometry with a chord of 0.023m. The Eppler 387 is actually an asymmetric airfoil, which can couple very well with the low Reynolds flow at the wing tip. Due to the dimensions of the cylindrical modules of the tip tank, the winglet root chord was fixed at 0.05m. Also, a taper ratio of 0.46 was adopted fixing the winglet tip chord as a function of span. The wind tunnel used was closed circuit with a test section of 1.3mx1.75m, a turbulence level of 0.25% and a maximum speed of 50m/s [21].

Spillman [4] got the best results for the tip-sails with 20% camber at the root. The camber decreases rapidly with the distance from the root to the winglet tip lessening approximately to a half part at each distance of 6% of the wing tip chord. In this way, it was established that the winglets would have a span of 0.105m. It was also established that the winglets would not have sweep at the 1/4 chord. The final winglet geometrical configuration can be seen in Fig. 18.

The lift and drag forces and aerodynamic efficiency were compared and better configurations were chosen, based on improvements in aerodynamic efficiency. Lift and drag forces were measured by a two-component balance. Due to the comparative analysis of the results no wall interference corrections were considered. The two-component balance used is of the strain gage type.

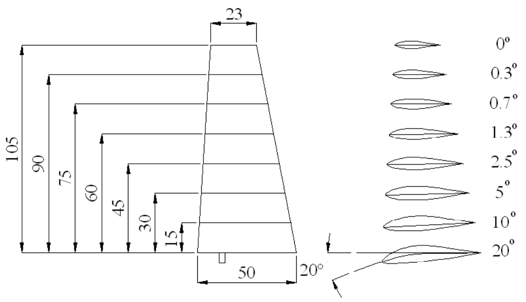

Fig. 18 Winglet final geometry

4.2 Results and Discussion

Only specific results are shown below, presenting the best results in induced drag reduction. Further details can be found in Cerï£¡-Muï£¡z and Catalano [22]. The results presented are always compared to the winglets-off case. The configurations selected,as shown in Fig. 19, are: a) Configuration 19: $+30°A$; $0°B$;$+30°C$, b) Configuration 48: $+45°A$;$+15°B$;$-15°C$, c) Configuration 47: $+60°A$;$+30°B$; $0°C$, d) Configuration 40: $+45°A$;$+30°B$;$+15°C$, e) Configuration 11: $-30°A$;$-15°B$; $0°C$, f) Configuration 44: $-15°A$;$-30°B$;$-45°C$

An increase in lift was achieved for all the selected configurations. This increase is larger for high incidence angles as shown in Fig. 20. The effect is almost independent of the configurations. Also lift curve inclination increased for all configurations up to 12 degrees, showing that the winglets increase both geometric and effective aspect ratio.

The selected configurations presented curves such as $CDx\alpha$ similar to those existent for the wing without winglet. However, more drag is produced at low incidence due to the increase in the aspect ratio with the presence of the winglets. Also for incidence angles above 16° the configurations showed larger drag coefficients, probably due to separation as shown in Fig. 21.

The increase in effective aspect ratio with the gain in lift led to a dramatic increase in the aerodynamic wing model efficiency as shown in Fig. 22.

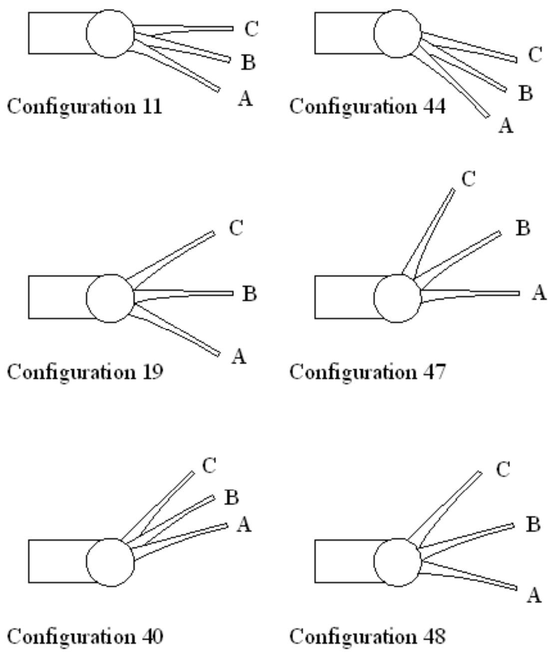

Fig. 19 Configurations considered better, A is the leading winglet, B is the central and C is the trailing one

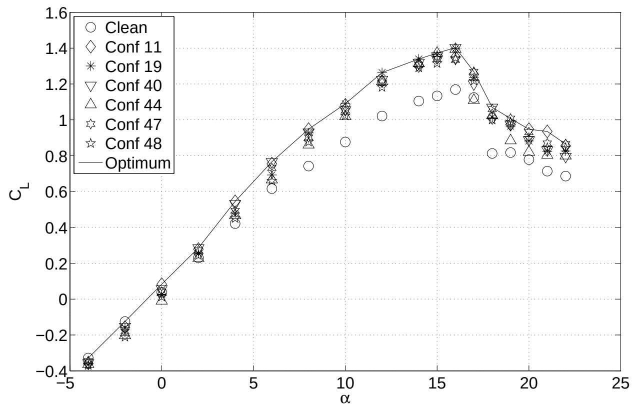

Fig. 20 Lift coefficient for the best configurations

In Fig. 23, the Drag polar also shows a great improvement for all configurations especially at high values of α.

In Fig. 24 the major parameter is the gradient $dC_D/dC_L{}^2$ taken from the linear part of the curve, this relates directly to the lift dependent induced drag C_{Di}. All the configurations improved the performance of wing induced drag and the curves are close.

From Fig. 24, it is clear that configuration 48

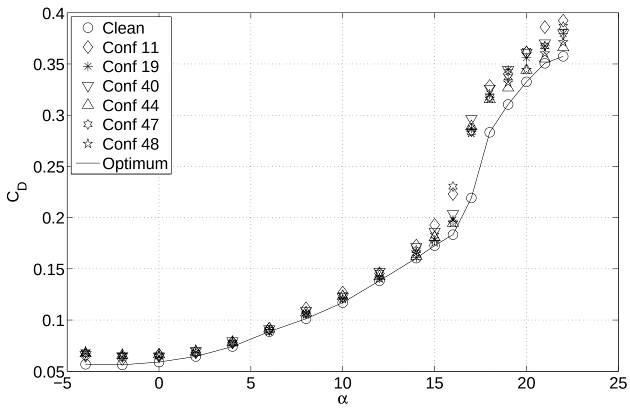

Fig. 21 Drag versus incidence angle

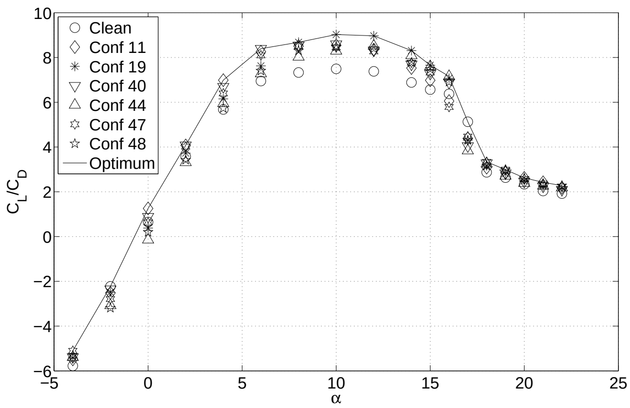

Fig. 22 Lift to drag curves

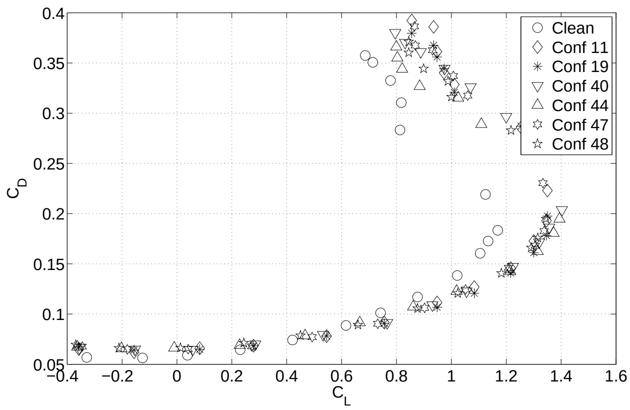

Fig. 23 Lift to drag curves

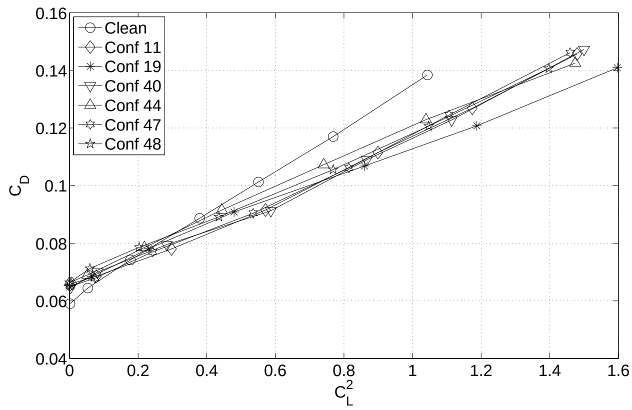

Fig. 24 Induced drag factor

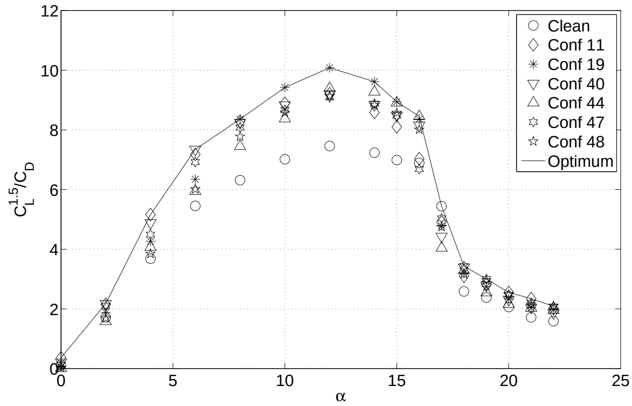

Fig. 25 Climb factor

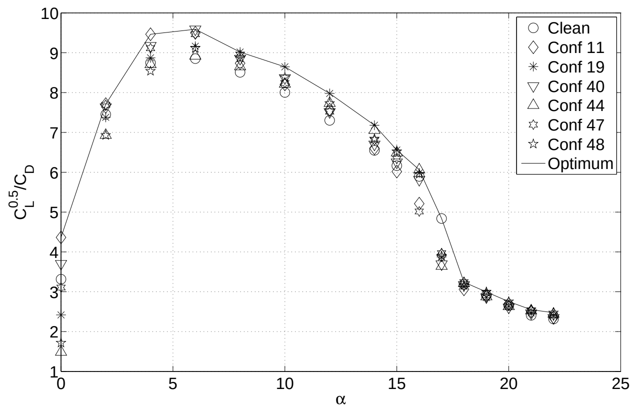

Fig. 26 Range factor

produced the smallest gradient and shows more advantages. The potential flexibility of operation of the adaptive multi-winglet system proposed is shown in Fig.25 and Fig. 26. It is possible to change the positions of the configurations in order to maintain the best performance with reference to climb rate and maximum range.

5 Conclusions

A group of experimental studies to investigate the effects of different wing tip devices on the reduction of induced drag were presented. From the experimental data the following conclusions can be drawn.

Whit regard to the use of delta tip, winglet, and "Hoerner" devices, concerning the aerodynamic characteristics of an agricultural airplane wing, all tip devices showed improvements to the aerodynamic characteristics of the wing. The best results were presented by the down curved tip, that equips up-to-date the Brazilian agricultural aircraft (EMBRAER-IPANEMA). Winglets improved the aerodynamic characteristics and the resultant tip vortex is very adequate for agricultural use but this device produces an undesirable increase of wing root bending moment. The Delta tip device produced moderate improvements on wing efficiency and is an economical choice for the increase of aircraft performance. However this tip is not adequate for agricultural applications because of the small vortex displacement in relation to other tip devices presented here. Therefore, the winglet offers the best potential capabilities for the development of a specific wing tip design for agricultural aircraft.

Wing tip blowing using a three vectored Coanda Jets combination was investigated. Results showed potential benefits in combining the three Jets with the aerodynamic characteristics of a wing. The optimization of the tip Jet flow for each operational maneuver may result in improvements for the whole flight envelope from climb to maximum range. However, some tests are still required at cruise configuration and low jet coefficients in order to accurately study the potential benefit of the three Coanda vectored Jets. Also some consideration and evaluation is still necessary to adapt this concept to the real world aircraft, such as the power bleeded from the engines to maintain efficient blowing; to low aspect ratio wings, a smart vectored system for the jets and so on.

An adaptive multi-winglet system was investigated using wind tunnel experiments in order to show the effect of the system on the aerodynamic characteristics of a low aspect ratio wing.It is not possible to say that the results of this study show a direct relationship between the effect of modifications to the tip vortex of a rectangular planform wing and the effect of these modifications on the induced drag of the entire aircraft in flight.

Induced drag is a function of the aerodynamic characteristics of the flow in the Treffts plane and modifications at the wing tip can influence the Treffts plane flow. Thus, this is not a one-to-one relationship. Proving these devices at entire aircraft, the true effects in the reduction of induced drag could be established. Nevertheless, it can be affirmed that the results showed potential benefits in combining a three winglet configuration with the particular aerodynamic characteristics of a wing. The optimization of the adaptive multi-winglet system for each operational mission may result in an improvement for the whole flight envelope from climb to maximum range. However, some tests are still required for the cruise configuration in order to accurately assess the potential benefits.

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