Proceedings of the 11th Brazilian Congress of Thermal Sciences and Engineering -- ENCIT 2006
Braz. Soc. of Mechanical Sciences and Engineering -- ABCM, Curitiba, Brazil, Dec. 5-8, 2006

Paper CIT06-0330

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

Hernán Darío Cerón-Muñoz
Aerodynamic Laboratory EESC-USP. Av. Trabalhador São-Carlense 400 São Carlos SP, Brazil
hernan@sc.usp.br

Rogério de Faria Coimbra
IFI-CTA. Av. Brigadeiro Faria Lima, 1.941 São José dos Campos SP, Brazil
rogerio@ifi.cta.br

Fernando Martini Catalano
Aerodynamic Laboratory EESC-USP. Av. Trabalhador São-Carlense 400 São Carlos SP, Brazil
catalano@sc.usp.br

Abstract. *A group of experimental studies were conducted to investigate the effects of different wing tip devices on the reduction of induced drag. The tests were conducted at the Aircraft Laboratory of São Carlos Engineering School (EESC) , and at the Aeronautical Laboratory of the Aeronautical Technical Institute (ITA), Brazil. In this work, wind tunnel test were made, the results are analzed in terms of lift and drag. The experiments were conducted in three stages:*

- *An analysis of the effect of delta tip, winglet, and "Hoerner" devices, concerning the aerodynamic chararacteristics of an agricultural airplane wing.*
- *The effect of wing tip blowing on vortex drag. This study tested lateral wing tip blowing device in which the jet flow exit was from three longitudinal slots on a wing tip model.*
- *Experimental Analysis of the aerodynamic characteristics of adaptative multi-winglets was performed. The aim of this stage is to study the potential use of adaptative multi-winglets for the reduction of induce drag using variations of winglet cant angle.*

Results showed that a delta tip wing is more promising for agricultural aircraf and the potential benefits in combining both the three jets and multi-winglets configurations with the aerodynamic characteristics of a wing.

Keyword: Induced drag, wing tip, winglets, blowing

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 (Henderson and Holmes, 1989). 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 (Kravchenco, 1996). Some of these devices such as winglets (Whitcomb, 1976), tip-sails (Spillman et al., 1978; 1979; 1984; 1987) and multi-winglets (Smith et al, 2001) 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 (1976) 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 (La Roche and Palffy, 1996). Kravchenco (1996) 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 (C_L), 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 (Coimbra and Catalano, 1999). For this category of aircraft, besides both aerodynamic and structural advantages, the influence of the vortices created during the mission of the aircraf is an added parameter in the analysis.

Winglets have been used to improve sailplane performance. Smith at al (2001) mentions the development work on winglets for sailplanes tested in a wind tunnel with scale models. 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 (2002) presented a methodology for the design of winglet airfoils.

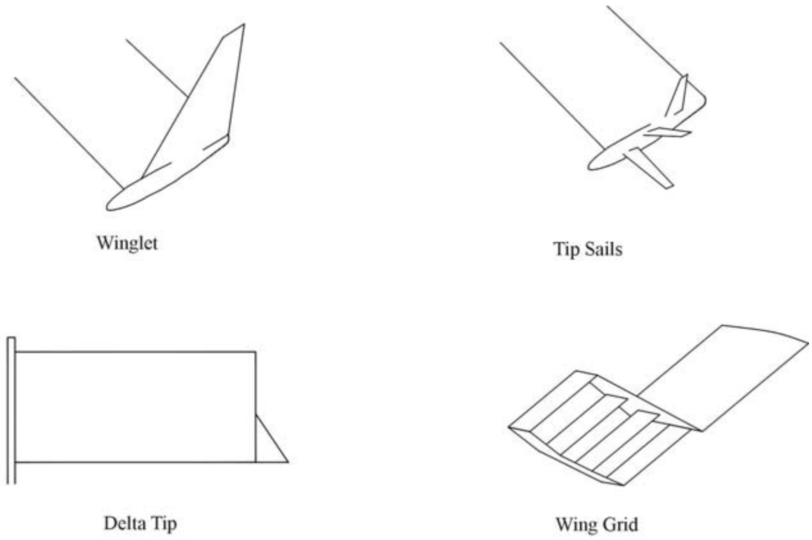

Figure. 1 Wing tip devices

Spillman et al.(1978, 1979, 1984, 1987), 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. (1978, 1979, 1984, 1944) also investigated the use of tip-sails installed on the tip-tank of a Paris MS 760 Trainer Aircraft (Spillman et al., 1978, 1979). 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 (Spillman et al., 1979). Also flight tests of a Cessna Centurion (Spillman and McVite, 1984) and a Piper Pawnee 235 (Spillman, 1987) 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 (Tavella, 1985, 1986; Wu and William, 1984 and Mineck, 1995) 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 et al. (2000) 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 (1978) with his tip sails.

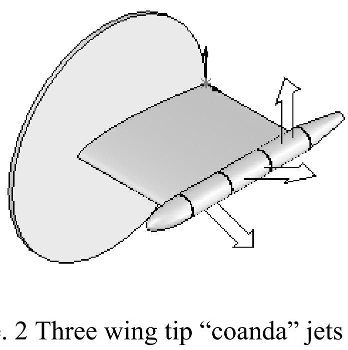

Figure. 2 Three wing tip “coanda” jets

2. An analysis of the effect of delta tip, winglet, and "Hoerner" devices, concerning the aerodynamic chararacteristics of an agrigultural airplane wing

In this stage, wind tunnel tests were made in order to study the influence on aerodynamic characteristics and vortex position, for Brazilian agricultural aircraft, using the following types of wing tips: delta tip, winglet and down curved. The down curved tip was better for total drag reduction, but not good with reference to vortex position. The delta tip gave moderate improvement on aerodynamic characteristics and on vortex position. The winglet had a better vortex position and lift increment, but caused an undesirable result with reference to the wing root bending moment. However, the winglet showed better development potential for agricultural aircraft.

2.1. Experimental Configuration

The tests were made at the University of São Paulo, Aircraft Laboratory, in an open circuit wind tunnel which has a hexagonal test section with a cross section area of 0,526 m² and 1,63 m 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 planform, without end caps, 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.

The delta tip was selected because of the good results shown recently (Traub, 1994), and for its structural simplicity. The winglet was chosen to be tested because of its successful use in commercial airplanes. The down curved tip was chosen to be compared, due to use in Brazilian agricultural aircraft. Figure 3 shows the tested models. The winglet, which was canted outward 20°, was tested at 5° incidence angle; and was constructed with a GA(W)-2 airfoil section, from wood, with a total winglet area of 12% of the wing area. The winglet planform was tapered with 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 down 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. The forces from the tests were corrected for blockage (Pope and Rae, 1984). Tare and interference effects, as well as the tunnel flow angularity, were established using an image system (Pope and Rae, 1984). The balance was unable to measure pitching moment. Tests were conducted at a freestream velocity of 28m/s. The set angle of attack was varied from 0 to 15 degrees. Wing Reynolds number was 2,7 x 10^5, based on chord length. A boundary-layer transition strip was fixed at 5% of the chord on the upper and lower surface along the entire wing span.

Wing root bending moments measurement were made also, to check any structural overloading or damage, using the same strain gage balance.

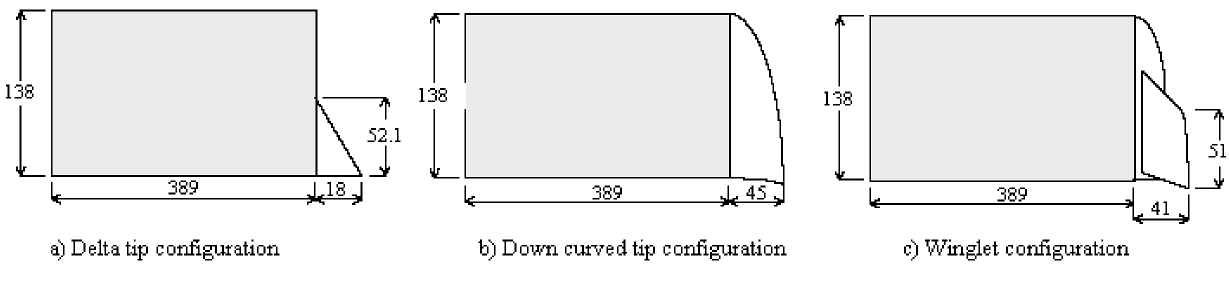

Figure. 3 Wing tip configurations

2.2. Results and Discussion

Table 1 contains a summary of the aerodynamic results. Figure (4) presented the aerodynamic characteristics of all configurations tested and shows the structural results. Figure (4) (a) presents the lift curves and shows an increase in lift coefficient for all tip configurations compared to the basic wing. Figure (5) (a) shows drag polar curves.

Table 1 Aerodynamics increments (%) due to win tip devices referring to basic wing

Parameters	Delta Tip	Down Curved Tip	Winglet
$dC_L/d\alpha$	+3.9	+11.1	+17.29
e	+1.63	+17.45	+45.43
C_{Lmax}	+1.75	+8.87	+8.96
L/D_{max}	+19.63	+34.21	+20.85
$C_L^{1.5}/C_D$ (max)	+17.32	+33.62	+22.41

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

$$C_D = C_{D\min} + C_L^{\,2} \big/ \pi \cdot AR \cdot e \tag{1}$$

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. The constant *e* incorporates both vortex and profile drag, which are difficult to separate as both vary with CL^2 . To calculate values of the Oswald efficiency for each of the wing tips tested, the relationship used was Eq. (2) (Nicks, 1983).

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

Where φ is the lift curve slope ratio.

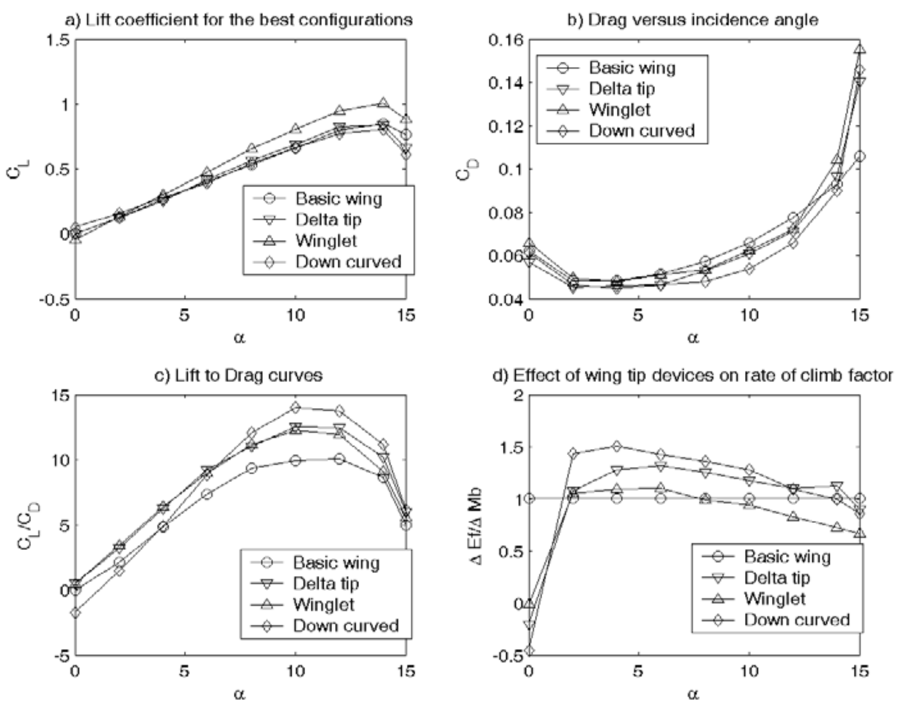

Figure. 4 Aerodynamics characteristics of Ipanema wing tip

Improvements in factor *e* directly affect the performance of the airplane, especially at high lift conditions. In Fig. (4) (b), at small angles of attack ($\alpha < 6°$), 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) (a) drag polar shows the same pattern presented in Fig (4) (b), 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. (4) (c) versus incidence. 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. 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. Figure (5) (b) shows rate of climb.

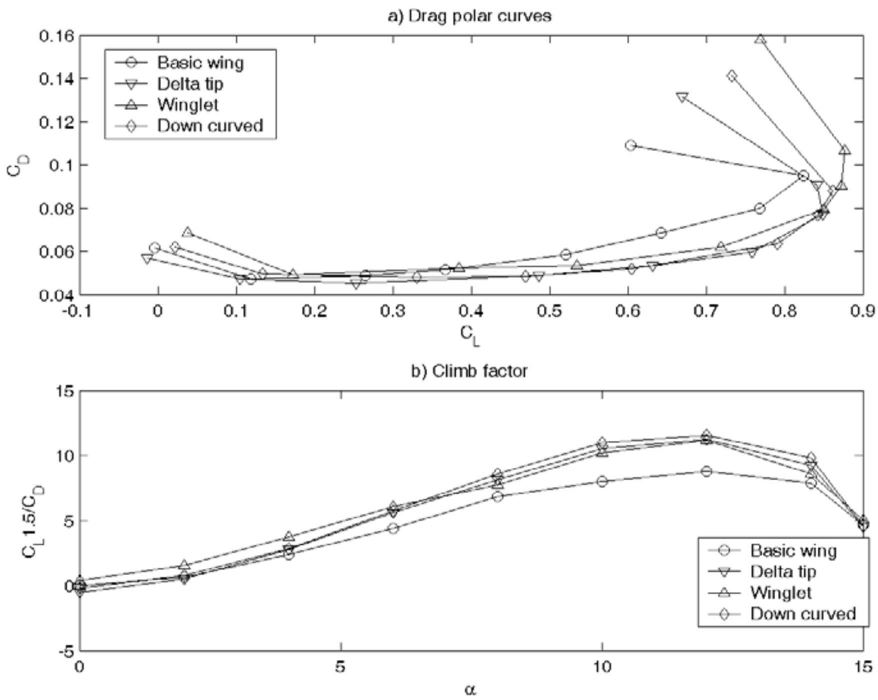

Figure. 5 Polar and range factor of Ipanema wing tip

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. Figure (4) (d) 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. 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. (4) (d), that only the winglet presents *ASEF* less than the unit for angles of attack higher than 8°.

3. Effect of wing tip blowing on the vortex drag

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 (no tip blowing) 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. 6.

Tests were conducted at the Aeronautical Laboratory of the Aeronautical Technical Institute in an open circuit wind tunnel with a 0.6 x 0.6 m 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.

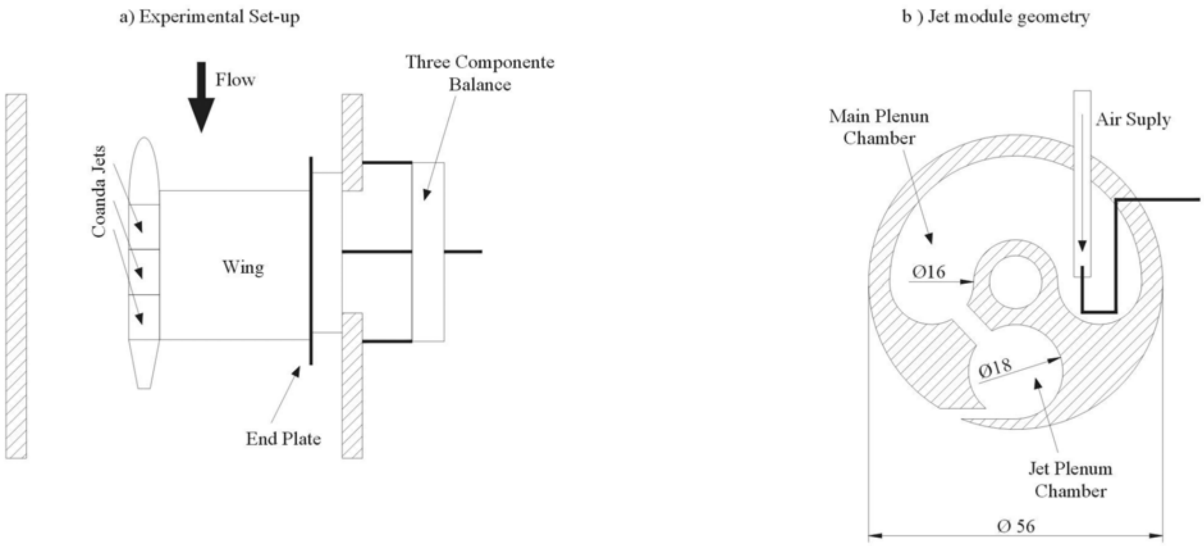

Figure. 6 Experimental set-up and jet module geometry

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^o from 0^o to 45^o for the first module, 0^o to 30^o for the central module and 0^o to 15^o for the rear module. The configuration nomenclature and reference positions are shown in Fig. (7). For example: tip blowing 1CY means that the first module is blowing at 0^o, central module at 30^o and rear module at 15^o.

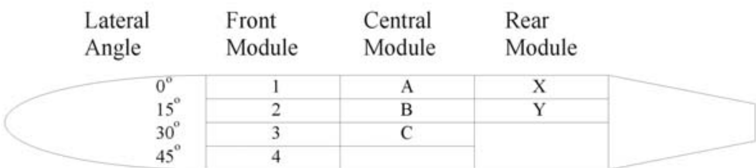

Figure. 7 Tip jet modules nomenclature

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

$$C_\mu = 2\frac{P_e}{q_\infty}\frac{S_j}{S_W} \tag{3}$$

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. Fig. (8) shows C_L x α and drag polar curves of the best results. As expected from previous work (Tavella et al 1985) (Simpson, et al 2000) 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.

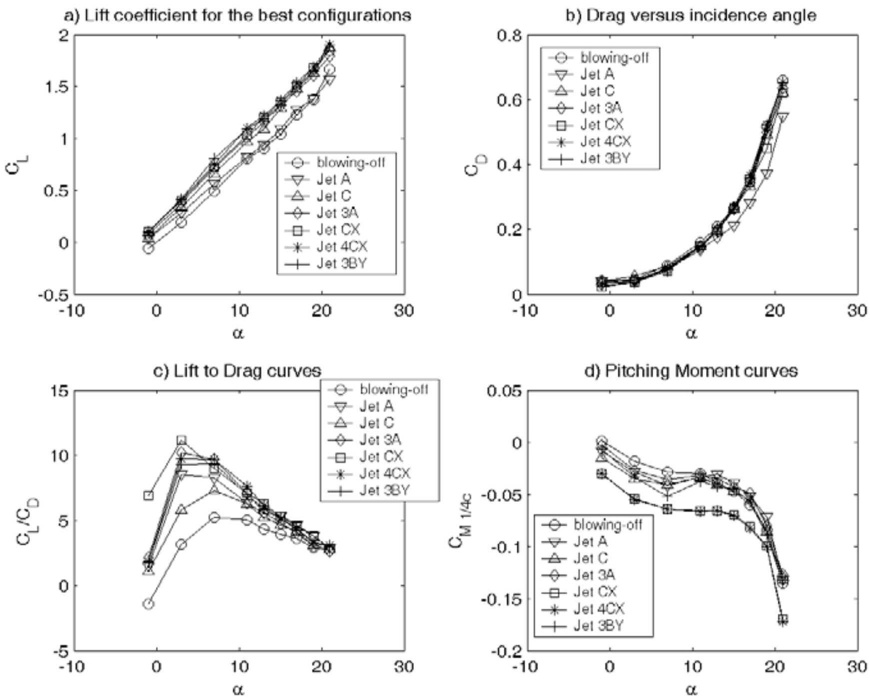

Figure. 8 Aerodynamics characteristics of win-tip blowing

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. (8)(a). At jet 3A the effect was still large but lift slope decreased. Drag results also shown in Fig. (8)(b) 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. (8)(c).

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. (8)(a) . This could be a result of an increase in effective aspect ratio but the weak shift of C_Lx α 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 also shows a large improvement for all jets especially at high incidences as shown in Fig. (9). The potential flexibility of operation of an active system as that proposed is shown in Fig. (9). 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. 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.

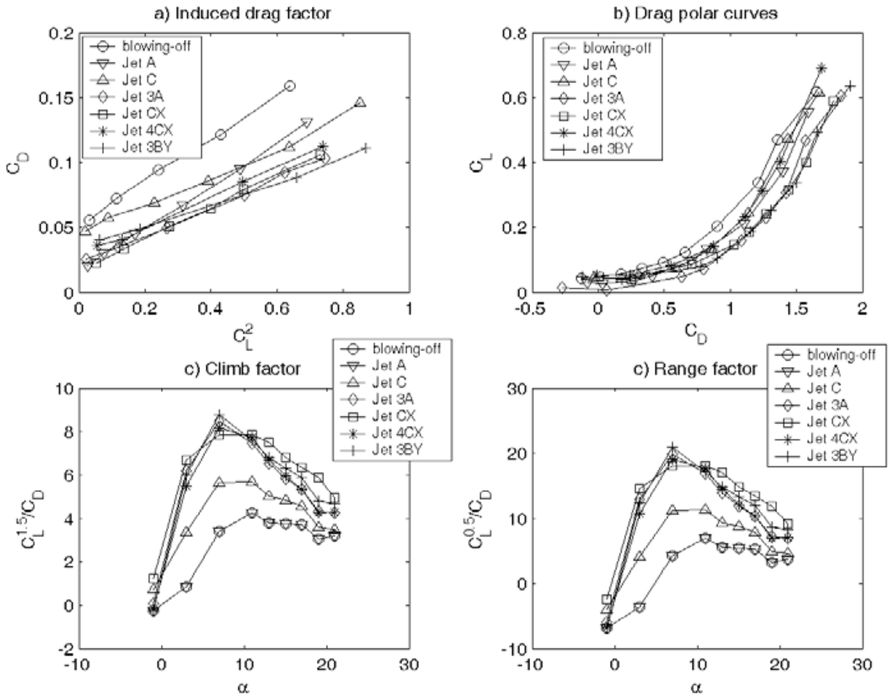

Figure. 9 Aerodynamics curves (wing tip blowing)

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 along the 25% chord line. The tests were made at a Reynolds number of 350,000. The results are analysed in terms of lift and drag. Results show that it is possible to find the best configuration of the three winglets in order to obtain the optimum aerodynamic performance for each flow regime in climb and cruise.

4.1. Experimental Configuration

The experimental model was a rectangular semi-span wing of 0.49 m with a chord of 0.25 m. For this study a tip tank with three vectorable cylindrical Coanda jets was developed (Coimbra and Catalano 2005). 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 0.05 m 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 0.023 m. 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 1.3 m x 1.75 m, a turbulence level of 0.25% and a maximum speed of 50 m/s (Catalano 2001).

Spillman (1978) 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 0.105 m. 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. (10).

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.

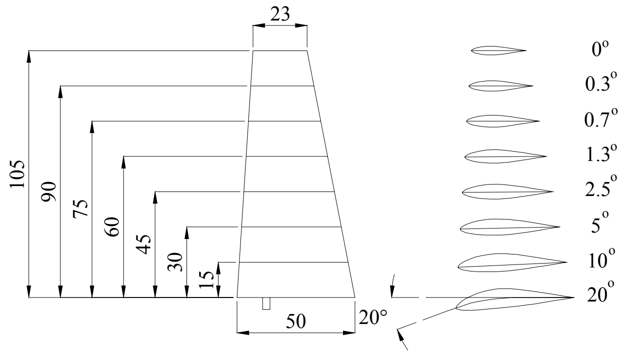

Figure. 10 Winglet final geometry

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 Cerón-Muñoz and Catalano (2006).

. However, a discussion will be presented with reference to the negative effects of each configuration. The results presented are always compared to the winglets-off case. The configurations selected are: Configuration 19: +30^o*A*; 0^o*B*;+30^o*C;* Configuration 48: +45^o*A*;+15^o*B*;-15^o*C,* Configuration 47: +60^o*A*;+30^o*B*; 0^o*C;* Configuration 40: +45^o*A*;+30^o*B*;+15^o*C;* Configuration 11: -30^o*A*;-15*oB*; 0^o*C;* Configuration 44: -15^o*A*;-30^o*B*;-45*oC* An increase in lift was achieved for all the selected configurations. This increase is larger for high incidence angles as shown in Fig. (11). 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.

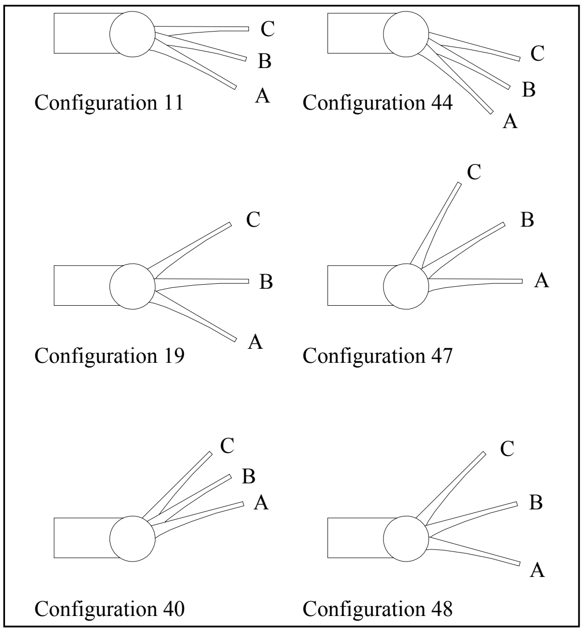

Figure. 11 Configurations considered better, A is the leading winglet, B is the central and C is the trailing one

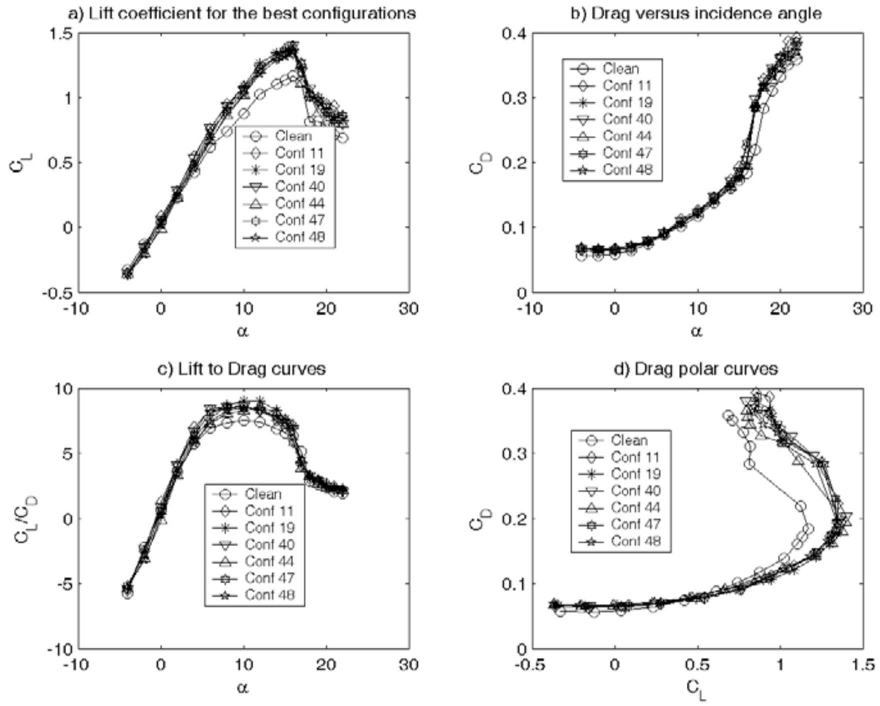

Figure. 12 Aerodynamics characteristics of multi-winglets

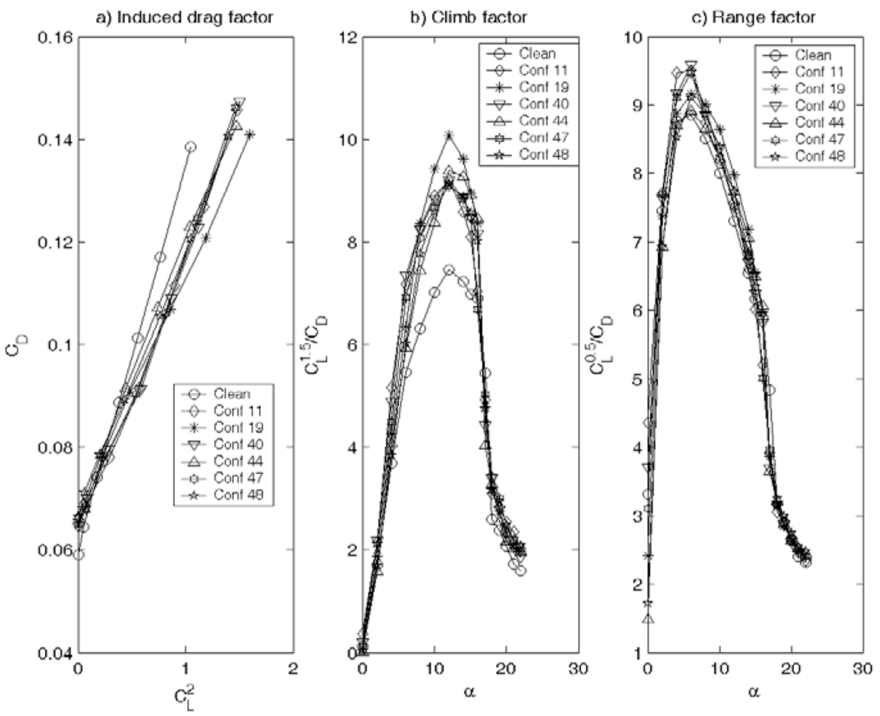

Figure. 13 Aerodynamics factors of multi-winglets

The selected configurations presented curves such as C_D *x* α 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^{o} the configurations showed larger drag coefficients as shown in Fig. (12), probably due to separation. 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. (12)(c). In Fig. (12)(d), the Drag polar also shows a great improvement for all configurations especially at high values of α..

In Fig. (13)(a) 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 and show a higher C_D for negative incidence angles. For these angles the configurations presented small dC_L/dC_L^2 gradients for the base tip. Also from Fig. (13)(b), it is clear that configuration 48 produced the smallest gradient and shows more advantages. The potential flexibility of operation of the adaptive multi-winglet system proposed is shown in Fig.(13). 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.

1). 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.

2). 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.

3.) 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. 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.

6. References

Catalano, F., 2001, "The New Closed Circuit Wind Tunnel of the Aircraft Laboratory of University of São Paulo", 16th Brazilian Congress of Mechanical Engineering. Vol.6, pp 306-312.

Cerón-Muñoz, H. D. and Catalano, F. M., 2006, "Experimental Analysis of the Aerodynamic Characteristics Adaptive of Multi-winglets", Journal of Aerosapce Engineering, Vol 220, No 3, pp. 209-216

Coimbra, R. and Catalano, F., 1999, "Estudo Experimental Sobre Pontas de Asa Para Uma Aeronave Agrícola", Revista Revista Brasileira de Engenharia Agrícola e Ambiental, Vol 3, No 1, pp. 99-105, 1999.

Coimbra, R. and Catalano, F., 2002, "Effect of wing tip blowing on the vortex drag", ICAS 2002 proceedings, Toronto, Canada.

Herderson, W. P. and Holmes, B. J., 1989, "Induced Drag: Historical Perspective", SAE paper n. 892341, Warrendale, PA. USA.

Kravchenco, S. A., 1996, "The Aplication of the Wing tip Lifting Surfaces for Practial Aerodynamic", ICAS-96-4.6.4, Sorrento Italy, pp. 1338-1349.

La Roche, U. And Palffy, S., 1996, "Wing-grid, a Novel Device for Reduction of Induced Drag on Wings",. ICAS-96-2.10, Sorrento Italy, pp. 2303-2309.

Maughmer, M. D., Swan, T. S. and Willits, S. M., 2002, "Design and Testing of a Winglet Airfoil for Low-speed Aircraft", Journal of Aircraft, Vol 39, No 4, pp. 654-661.

Mineck, R. E., 1995, "Stydy of Potential Aerodynamic Benefits from Spanwise Blowing at Wing tips", NASA TP No. 3515, pp. 97.

Nicks, O. W., 1983, " Wing Extension for Improving Climb Performance", AIAA paper 83-2556.

Pope, A. and Rae, W. H., 1984, "Low Speed Wind Tunnel Testing", Wiley, New York.

Simpson, G., Ahmed, N. A. and Archer, R. D., 2000, "Improvement of a Wing's Aerodynamic Efficiency Using Coanda Tip Jets", Journal of Aircraft, Vol. 37 No.1, pp. 183-184.

Smith, M. J. et al., 2001, "Performance Analysis of a Wing with Multiple Winglets", AIAA paper 2001-2407.

Spillman, J. J., 1978, "The Use of Wing tip Sails tu Reduce Vortex Drag", Aeronautical Journal, Vol 82, No 813, pp. 387-395.

Spillman, J. J., Ratcliffe, H.Y. and McVitie, A. 1979, "Flight Experiments to Evaluate the Effect of Eing-tip Sails on Fuel Consumption and Handling Characteristics", Aeronautical Journal, Vol. 83, No. 823, pp. 279-281.

Spillman, J, J. and McVitie, M. 1984, "Wing tip Sails Which Give Lower Drag at All Normal Flight Speeds", Aeronautical Journal, Vol. 88, No. 878, pp. 362-369.

Spillman, J. J., 1987, "Wing tip Sails; Progress to Date and Future Developments", Aeronautical Journal, Vol 91 No 910, pp 445-543.

Tavella, D., 1985, "Measurements on Wing Tip Blowing", NASA CR-176930, pp. 36.

Tavella, D., et al., 1986, " The Iinfluence of Tip Blowing on Rectangular Wings", AIAA paper no. 85-5001.

Traub, L. W., 1994, "Aerodynamics Effects of Delta Planform Tip Sail on Wing Performance", Journal of Aircraft, Vol.31, No 5, pp. 1156-1159.

Whitcomb, R. T., 1976, "A Design Approach and Selected Wind-tunnel Results at High Subsonic Speeds for Wing tip Mounted Winglets", NASA Technical note D-8260, pp. 3-27.

Wu, J. M., Vakili, A. D., and William, F., 1984, "Aerodynamic Interaction of Wing Tip Flow With Discrete Wing tip Jets", AIAA paper no. 84-2206.