AN EXPERIMENTAL STUDY ON WINGTIP DEVICES FOR AGRICULTURAL AIRCRAFT

Rogério F. F. Coimbra[§] and Fernando M. Catalano*
Aircraft´s Laboratory, University of São Paulo, São Carlos, BRAZIL

Abstract

The induced drag is responsible for nearly 50% of aircraft total drag and can be reduced through modifications to the wing tip. Some models displace wingtips vortices outwards diminishing the induced drag. Concerning agricultural airplanes, wing tip vortex position is really important, while spreading products over a plantation. In this work, wind tunnel tests were made in order to study the influence in aerodynamic characteristics and vortex position, over Brazilian agricultural aircraft, by 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 referring to vortex position. The delta tip gave moderate improvement on aerodynamic characteristic and on vortex position. The winglet had a better vortex position and lift increment, but caused an undesirable result referring to the wing root bending moment. However, winglet showed better development potential for agricultural aircraft.

Nomenclature

ASEF	aerodynamic-structural efficiency factor, $ASEF = \Delta E_f / \Delta M_b$
AR	wing aspect ratio
b	wing span
b_T	wing tip span
c	wing chord
C_D	drag coefficient
C_{Dmin}	minimum drag coefficient
C_L	lift coefficient
C_{Lmax}	maximum lift coefficient
$dC_L/d\alpha$	wing lift curve slope
$(dC_L/d\alpha)_\infty$	wing profile lift curve slope
Di	induced drag
e	Oswald efficiency factor
L	lift
L/b	wing span loading
L/D	aerodynamic efficiency
$(L/D)_b$	basic wing aerodynamic efficiency
M_b	wing configuration root bending moment
$M_{b\,b}$	basic wing root bending moment
α	wing angle of attack or incidence
ΔE_f	wing configuration aerodynamic efficiency factor, $\Delta E_f = (L/D)/(L/D)_b$
ΔM_b	wing configuration root bending moment factor, $\Delta M_b = M_b / M_{b\,b}$
φ	lift curve slope ratio, $\varphi = (dC_L/d\alpha)_\infty / (dC_L/d\alpha)$

1 Introduction

With the increasing need for fuel economy, all possible areas of drag reduction need to be investigated. A form which offers considerable promise is the induced drag. Induced drag is associated with the shedding of vorticity along the span of a finite lifting wing and, in particular, in the wingtip region. For most subsonic airplane configurations, induced drag contributes nearly 50% of the total drag in optimum cruising flight and contributes much more than 50% of the total drag in climbing

[§] Doctorate Student, University of São Paulo
* Ph.D. Professor, University of São Paulo

flight. Consequently, a strong interest has always existed in the effects of wing planform and wingtip shape on induced drag, because any reduction on the induced drag would directly reduce the operating costs of existing aircraft.

It is well know that induced drag D_i is a function of the square of the span loading: $D_i \propto (L / b)^2$. The level of the induced drag can be decreased by increasing the wing span b for constant lift L. When the wing span is constrained, induced drag reduction can be achieved by improving the aerodynamic efficiency of the wing, which would allow an aircraft to have lower wing areas and weight. Past researches efforts have resulted in several successful aerodynamic concepts, including endplates [1,2], winglets [3], tip-sails [4,5] and vortex diffusers [6]. The potential gains from some of these devices are limited by the wing-root-bending-moment and wetted-area considerations.

In generating lift the wing of an aircraft causes the airflow near each wingtip to swirl round the tip from lower to upper surface. This swirling motion increase is directly proportional to the increase of the wing lift and varies an inverse relation to the aircraft speed at a given lift and flying height. Thus, a crop spraying aircraft, which is generally heavy loaded and has to fly relatively slowly, generates a strong swirling motion near each wingtip. If the aircraft has nozzles near this tips, the spray from them will be swept into these swirling flows, and some of it will be thrown into the air above and behind the tips, to be blown away from the target area, if there is slight cross wind, causing serious environmental damage adjacent to the working area. Even if the spray boom is significantly smaller than the wing span, the smaller droplets from the outer nozzles can be entrained and thrown upwards. With volatile sprays, such as those with a large water content, evaporation can occur so quickly, that quite a large number of the smaller sized droplets generated can be affected. If the aircraft flies close to the crop, ground proximity effect materially increases the swirl velocity. In this work, wind tunnel tests were made, in order to study the influence in aerodynamic and structural characteristics and vortex position, over Brazilian agricultural aircraft, by the following types of wing tips: delta tip, winglet and down curved. The results and discussion are presented below.

2 Experimental Apparatus and Procedure

The tests were made at Aircraft's Laboratory in University of São Paulo, during spring of 1996, in an open circuit wind tunnel which has 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 original airfoil. The wing model has 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 wing tips tested were 'delta tip', 'winglet' and 'down curved tip'. The delta tip was selected because of its good results shown recently [7], and for its structural simplicity. The winglet was chosen to be tested because of its successful use in commercial planes. The down curved tip was chosen to be compared for its use in Brazilian agricultural aircraft. Figure 1 shows the tested models and Table 1, the geometric characteristics.

The winglet, which was canted outward 20°, was tested at 5° incidence angle; and it 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° sweep angle; its root chord and span had the same geometric value: 66,6% of wings 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 its root chord was corresponding at 37,7% of the wing chord. The leading edge of the delta tip was sharp to enforce flow separation.

Both configurations were positioned near of 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 and your repeatability was estimated at

$$C_L = \pm 0,003$$
$$C_D = \pm 0,001$$

The forces from the tests were corrected for blockage [8]. Tare and interference effects, as well as the tunnel flow angularity, were established using an image system [8]. The balance was not able to measure pitching moment. Tests were conducted at a freestream velocity of ~ 28m/s (equivalent to a Mach number of ~ 0,08). The set angle of attack was varied from 0 to 15 degrees. The wing Reynolds number was 2,7 x 10^5, based on a reference chord length of 138mm. The forces were nondimensionalized using their respective planform area. Boundary-layer transition strip was fixed at 5% of the chord on the upper and lower surface along the entire wing span.

Smoke visualizations were made to verify the wing tip vortex position (because of its importance to aerial crop spraying operations) as well as surface visualizations were made to verify the wing's flow. Wing root bending moments measurements were made also, to check any structural overloading or damage, using the same strain gage balance.

3 Experimental Results

Table 2 contain a summary of the aerodynamics results. Figures from 2 to 6 presented the aerodynamic characteristics of all configurations tested. Figure 7 shows the structural results and Figure 8 the smoke visualizations.

3.1 Aerodynamic Results

Figure 2 presented the lift curves and shows an increase in lift coefficient for all tips configurations compared to the basic wing. The lift curve slope, $dC_L/d\alpha$, was increased by 3,9%, 11,1% and 17,3% over the basic wing for the delta tip, down curved tip and winglet, respectively. The maximum lift coefficient was shifted by 8,9% for the winglet and down curved tip; the delta tip shown little effect on C_{Lmax} .

Figures 3 and 4 show drag curves and drag polars, respectively. To quantify the induced drag performance in the most useful lift range, the drag polar may be approximated by:

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

Where C_{Dmin} is the minimum drag coefficient, and e is the Oswald efficiency factor. The first effect in the induced drag is primarily due to lift and can be thought of as a change in 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 C_L^2 . To calculate values of the Oswald efficiency for each of the wing tips tested, the relationship used was [9]:

$$e = 57,3.(dC_L/d\alpha_\infty)/[(\varphi - 1).\pi.. AR] \qquad (2)$$

Improvements in factor e directly affect the performance of the airplane, especially at high lift conditions.

In Figure 3, at small angles of attack ($\alpha < 6°$), the delta tip device shows less drag than the others wing-tips configurations; at higher incidences, down curved tip presents smaller drag coefficients. In Figure 4 drag polars showed the same pattern presented in Figure 3, at lift coefficients 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 C_L's from 0,4 to 0,8 the winglet drag equals to the delta tip values. At much higher lift coefficients, winglet has a small advantage over the down curved tip.

The Oswald efficiency factor *e* shown increment of 1,6% for delta tip, 17,4% for down curved tip and 45,4% for winglet, when compared with basic wing ($e = 0{,}567$). It should be noted that, the addition of the tested tips increased the geometric aspect ratio of the basic wing and this was carried on consideration for the Oswald efficiency factor calculus. The increment of the aspect ratio was: 9%, 14,7% and 11% for delta tip, down curved tip and winglet, respectively.

The aerodynamic efficiency (L/D ratio) is presented in Figure 5 versus incidence. At angles of attack less than 7°, the winglet shows better L/D ratio; after this incidence, down curved tip presents better aerodynamic efficiency. The factor L/D is primarily responsible for aircraft glide ratio, cruise and range.

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. All combine into a relationship for rate of climb and the key aerodynamic parameter to measure the wing tips effects on rate of climb [9] is: $C_L^{3/2}/C_D$. Figure 6 shows the variation of the rate of climb parameter versus angle of attack. At incidences less than 8°, winglet offers better results; at higher incidences down curved tip was better. The maximum rate of climb was increased by 17,3% for delta tip, 22,4% for winglet and 33,6% for down curved tip, when compared with basic wing.

3.2 Structural Results

All aerodynamics benefits had its importance reduced, if structural damages are caused in wing by the addition of the wing tips. Then, structural reinforcements are needed, increasing the wing weight and reducing fuel capacity and payload.

Figure 7 presents the parameter ΔE_f / ΔM_b. This parameter, called *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 (ΔE_f) and its root bending moment (ΔM_b) is compared with the basic wing at each incidence angle; then the basic wing has its parameter equals to the unit at all angles of attack range. If *ASEF* is higher than the unit, then the wing tip configuration is providing more beneficial increments on wing efficiency than structural damage. If *ASEF* is lower, then the wing tip configuration causes more structural overloads than aerodynamic benefits. It can be noted, in Figure 7, that only the winglet presents *ASEF* less than the unit for angles of attack higher than 8°.

3.3 Wing Tip Vortex Position Results

The smoke flow visualizations was made to verify the wing tip vortex position, that has great importance to the aerial crop spraying applications. With a light sheet positioned at one chord distance from the trailing edge, the vortex core was visualized and recorded by photographs. Figure 8 presents these results. Delta tip configuration displaces the vortex core outwards. The winglet displaces it outwards and upwards. The higher wing tip vortex displacement outward is presented by down curved tip, but this tip moves the core downward too. All these displacements causes increment on wing effective aspect ratio and are related directly with the increments on wing aerodynamic characteristics.

4 Discussion of Results

4.1 Down Curved Tip

The down curved tips are frequently used now because they protect the wing tip and ailerons from contact with the ground. Aerodynamically, they are good, tending to confine the high pressure air and restrict its movement round to the upper side. The tip vortex might form just outboard of the tip [10]. These characteristics can be verified through presented results. All these characteristics produces the better overall aerodynamic results when compared with delta tip and winglet. However, its tip vortex position is not adequate to aerial crop spraying applications because the vortex is displaced downwards, near the spray nozzles. Then, large amounts of agricultural products sprayed by the aircraft are carried off target.

4.2 Winglet

Winglets are a kind of end plates but are different in principle. An end plate is intended to restrict or prevent the tip vortex. Winglets are designed to use the vortex by extracting some of its energy. This not only weakens the vortex but, it is capable to produce a force that have a forward-acting component (thrust) [3,10]. If the vortex strength is strong enough, the winglet is effective in reducing the overall drag. Since winglets produce lift, each winglet has a vortex at its own tip and this tip vortex is less intense than the main wing vortex without winglets. Therefore, some saving in drag will be gained. All this benefits can be appreciated in acquired preview results. However, others force's components produced at winglet are responsible for the increase of bending loads on the wing main structure. This characteristic is well defined in Figure 7.

Previous studies [11] has indicated that there are others potential problems associated with winglets; these problems are: poor lateral-directional dynamic behavior and handling qualities characteristics. One possible way of providing improved lateral-directional control response characteristics and reducing structural damages of the winglet configuration, would be to reduce the size of the winglet, but this approach may degrade the favorable benefits in wake interaction and aerodynamic performance.

Much additional research is required, however, before the effectiveness of winglets in aerial application can be properly evaluated in terms of aerodynamics, wake-interaction, structural behavior and aircraft handling qualities.

4.3 Delta tip

Delta tip produced moderate improvements in wing efficiency. The lift increments are most likely associated with the high-flow angularity and induced velocities in the vicinity of the wing tip in which the delta tip are situated; these induced velocities displace the tip vortex outward and improve the wing effective aspect ratio [7].

Delta tips are flat, slender, sharp-edged delta planform tip device and, in comparison with winglets, they have some advantages: they don't need to be cambered and washed-in because they don't require attached flow. In fact, they use enforced flow separation but, although this result in loss of leading edge thrust and growth in vortex drag, these can be partially recovered as vortex lift [7].

Delta tip devices are simple, inexpensive, easy to construct and adopt in any wing tip, and they don't produce any structural overload. Although these all beneficial characteristics this tip device is not adequate to aerial applications because its tip vortex position has moderate displacement outward when compared with others tested tip devices.

5 Conclusions

An experimental investigation to determine the effects of tip devices on the aerodynamic and structural characteristics of a wing representative of Brazilian agricultural aircraft, was presented.

From the experimental data the following conclusions can be drawn. All tip devices shown increment on aerodynamic characteristics of the wing. The best results was presented by down curved tip, that equipped up to date the Brazilian agricultural aircraft. However, this wing tip displaces the vortex downward damaging the aerial crop spraying applications. Winglets has good increments on aerodynamic characteristics too and its tip vortex is very well adequate to agricultural use but, this device produces an undesirable increment on wing root bending moment. Delta tip device produces moderate improvements on wing efficiency and is an economical choice to increase aircraft performance. However this tip is not adequate to agricultural applications because its small vortex displacement in relation to others tip devices presented here. Therefore, winglet offers the best potential capabilities to development of a specific wing tip design to agricultural aircraft.

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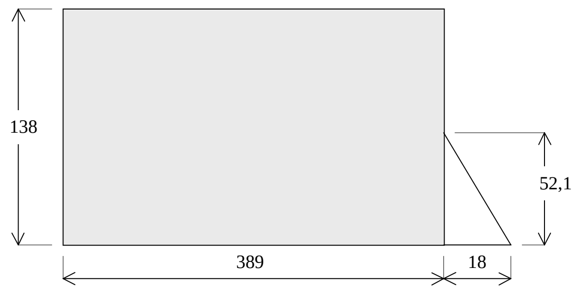
Table 1 Geometric parameters of wing tip configurations

PARAMETER	BASIC WING	DELTA TIP	DOWN CURVED TIP	WINGLET
SPAN (m)	0,389	0,407	0,434	0,430
TOTAL WING AREA (m²)	0,0536	0,0541	0,0582	0,0591
ASPECT RATIO	5,63	6,14	6,46	6,25
ASPECT RATIO INCREMENT (%)	---	9	14,7	11

Table 2 Aerodynamics increments (%) due to wing tip devices referring to basic wing

PARAMETERS	DELTA TIP	DOWN CURVED TIP	WINGLET
$dC_L/d\alpha$	+3,90	+11,10	+17,29
e	+1,63	+17,45	+45,43
C_L máx	+1,75	+8,87	+8,96
L/D máx	+19,63	+34,21	+20,85
$C_L^{1,5}/C_D$ máx	+17,32	+33,62	+22,41

a) Delta tip configuration



b) Down curved tip configuration

c) Winglet configuration

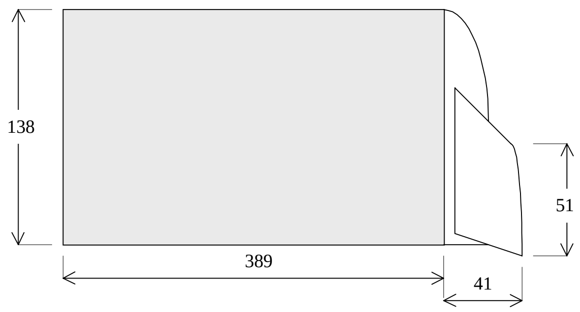


Fig. 1 a),b),c). Wing tip configurations studied (dimensions are in millimeters)

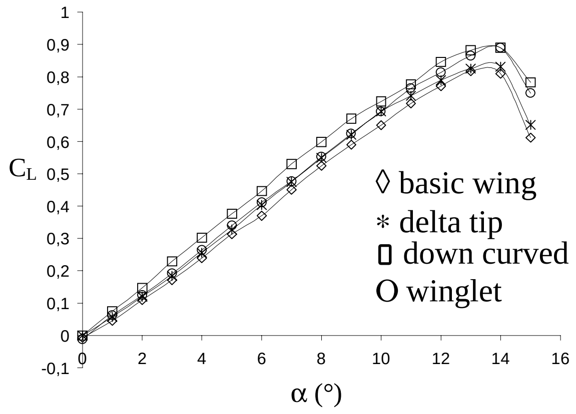


Fig. 2 Effect of wing tip devices on lift coefficient

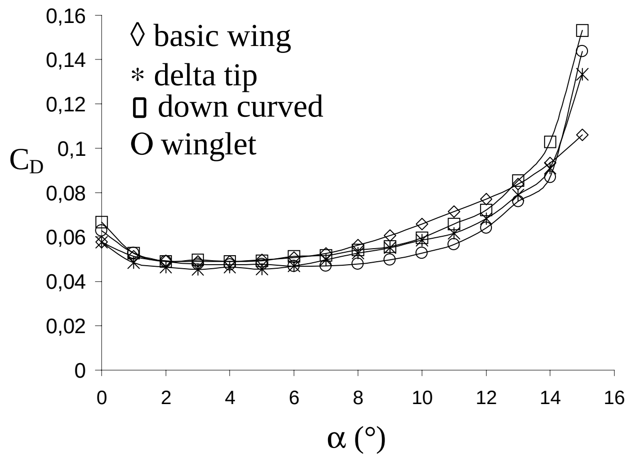


Fig. 3 Effect of wing tip devices on drag coefficients

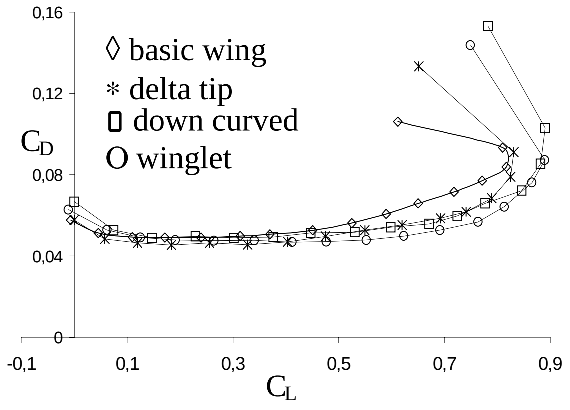


Fig. 4 Effect of wing tip devices on drag polar

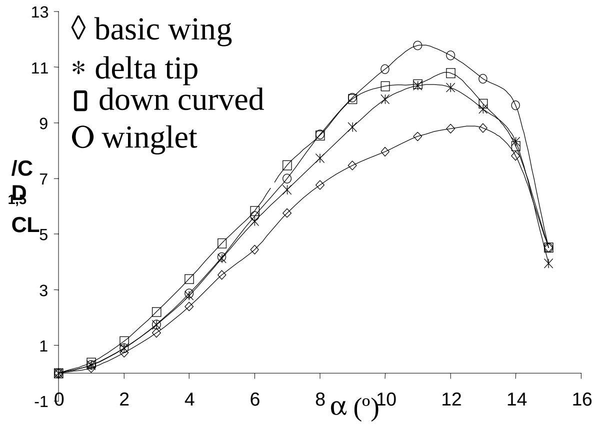


Fig. 6 Effect of wing tip devices on rate of climb factor

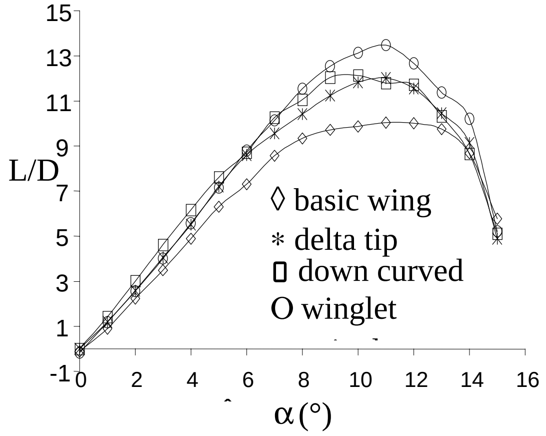


Fig. 5 Effect of wing tip devices on aerodynamic efficiency

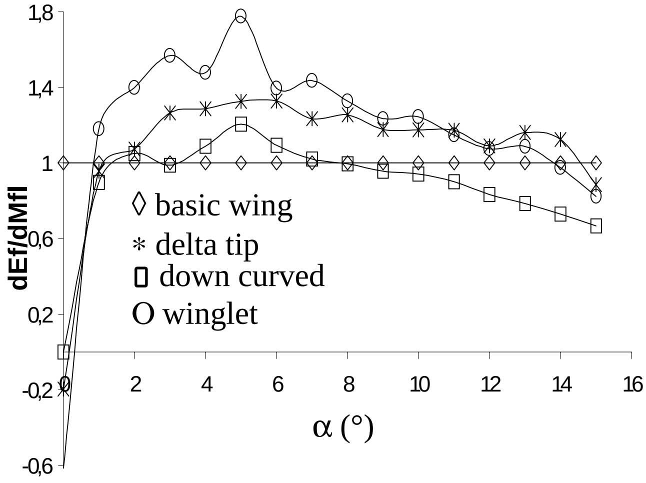
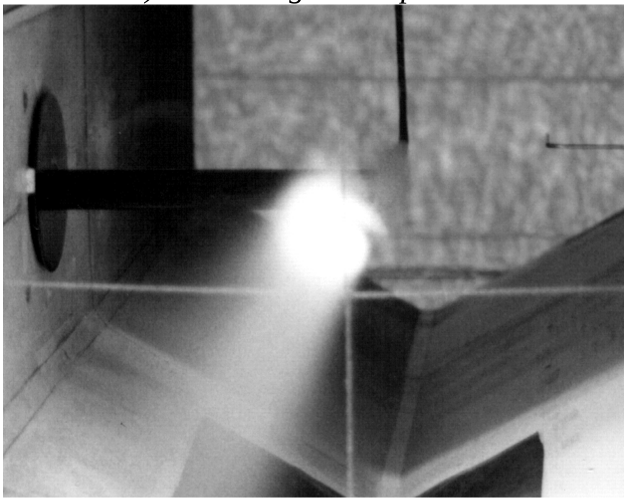
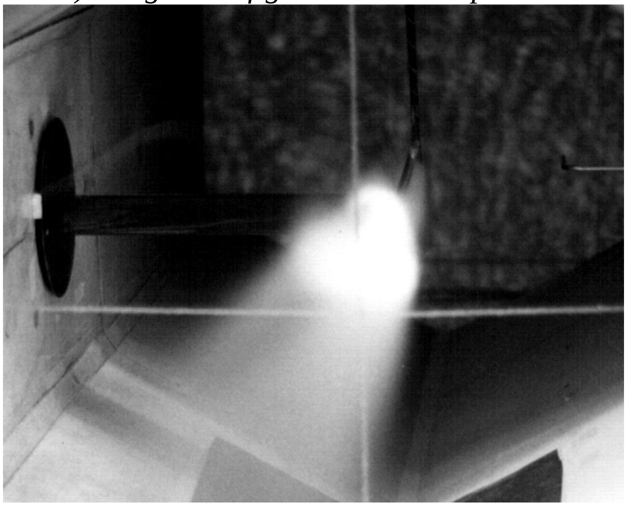


Fig. 7 Effect of wing tip devices on ASEF parameter

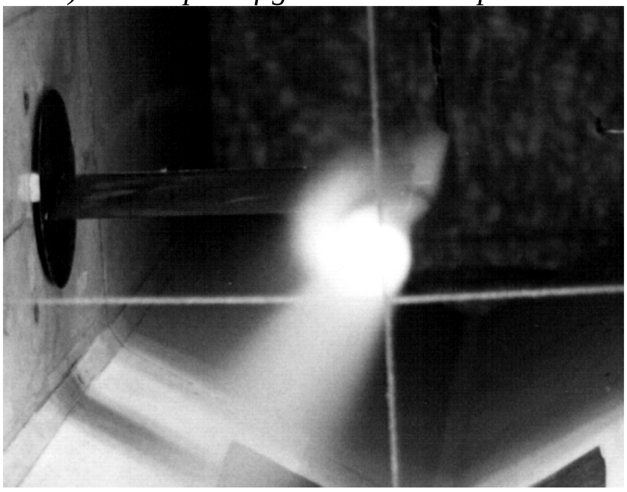
a) Basic wing vortex position



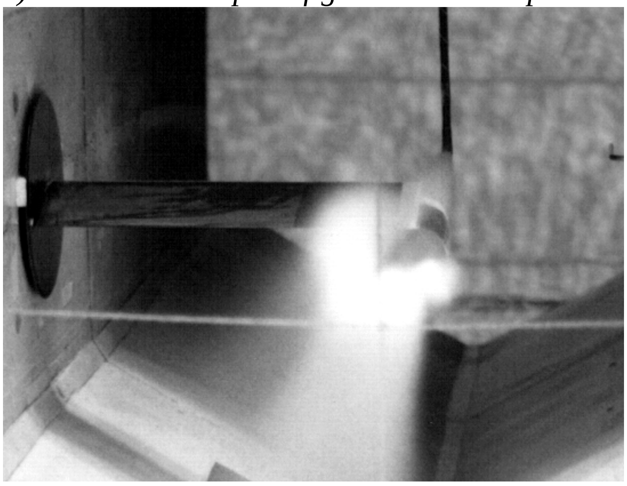
d) Winglet configuration vortex position



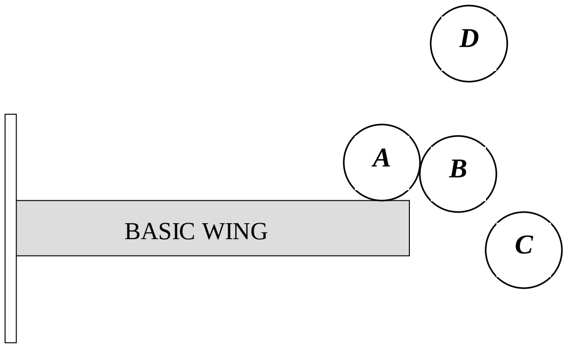
b) Delta tip configuration vortex position



c) Down curved tip configuration vortex position



e) Comparative sketch of wing tips vortex positions



A *- loci of basic wing tip vortex*
B *- loci of delta tip vortex*
C *- loci of down curved tip vortex*
D *- loci of winglet tip vortex*

Fig. 8 a), b), c), d), e) Wing tip vortex position