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# VORTEX GENERATOR EFFECT ON LOW REYNOLDS NUMBER AIRFOILS IN TURBULENT FLOW

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**Keywords:** Turbulent flow, Low Reynolds numbers, Airfoil, Vortex generators.

**Abstract:** *The purpose of this work is to study, in turbulent flow conditions, the effect of triangular vortex generators placed on the upper surface of an airfoil, on its aerodynamic coefficients. Those vortex generators were used as passive flow control devices. In the experiments, different configurations of those devices have been studied. Their positions respect to the leading edge and their incidence angles have been varied.*
*A low Reynolds number airfoil Eppler 387, modified, was used. The tests were performed in a turbulent boundary layer wind tunnel using a two components aerodynamic balance and flow visualization systems.*

## 1 INTRODUCTION

Flow control on a body means all kinds of mechanisms or processes to change the flow behavior in the surroundings and downstream of the body, in relation with the flow behavior without such devices and/or mechanisms in the body.

In such way, flow control involves passive and active devices which induce a beneficial change in wall flows and/or shear flow. The passive systems do not need an expense of extra energy unlike the active methods Ref. [1].

The goal of the flow control is to achieve, at least one of the following features: to increase the lift; to decrease the drag; to delay and/or advance the laminar-turbulent boundary layer transition; to avoid and/or delay the stall; to increase or decrease the turbulence over the body and to prevent or provoke the stall Ref. [2] [3] [4]. Some of the purposes of the flow control are to reduce the aerodynamic drag Ref. [5], to increase the lift, to increase the flow mixing and/or to induce the reduction of the noise applying fluid dynamics methods.

On lift surfaces at low Reynolds flow (Reynolds number between 10.000 and 1.000.000 based on the free upstream velocity and on the chord of the wing or airfoil), the appearance of a separation bubble on the upper surface can modify decisively the flow field. Ref. [6]

In the low Reynolds numbers range, the flow on the upper surface of an airfoil at a given angle of attack appears to be very complex. If the airfoil surface is polished the boundary layer remains laminar until the pressure gradient changes its sign. Besides, due this can bring variations in the airfoil performance, the region of laminar flow that offers less resistance to the separation that the turbulent one. The separated flow generates a free shear layer that is highly unstable, coming to a rapid transition to turbulence. In these conditions the flow can re-attach due to the increasing income of external turbulent flow towards the region near the wall. Due the consequent energizing of the recirculation flow, a separation bubble being constituted. The conditions for the appearance of this laminar bubble are dependent from different factors including: the Reynolds number, the pressure distribution, the surface curvature and roughness, the turbulence of the upstream flow as well as other environmental factors Ref. [7].

In low Reynolds numbers range, the separated flow is oriented in a direction tangent to the airfoil surface in the separation point. The entrance of a turbulent flow jet from the free stream induces the reattachment of the flow, constituting the laminar bubble already mentioned. Downstream from the point of reattachment, the recently formed turbulent boundary layer has more available energy to fight against the adverse pressure gradient avoiding the separation. The turbulent boundary layer's capability to resist the separation is enhanced as the Reynolds number grows Ref. [8].

The question that arises on these topics is how to control the flow in a low Reynolds number airfoil Ref. [9], with the objective of increasing its performance. The major success of the flow control techniques have been observed, when they produce phenomena such like laminar separation, followed by flow reattachment on the upper surface of the airfoil. Ref. [10]

In these conditions, the flow control can be achieved by using different devices such like turbulators, vortex generators, boundary layer suction and blowing, etc., in either active or passive form Ref. [11] [12] [13].

Turbulators and vortex generators are commonly used as passive flow control devices. Despite their similar geometries, they have some important differences Ref. [14] [15].

A turbulator acts on the airfoil boundary layer modifying its characteristics, by producing a perturbation that turns it turbulent and more energetic, delaying the stall condition and enhancing the circulation around the airfoil producing a stronger lift force Ref. [16]. For those reasons, in order to obtain the desired effect, turbulators should be smaller than the airfoil boundary layer thickness in the place where they are located.

On the other side, a vortex generator acts in the flow around the airfoil, modifying the flow pattern by means of the generation of small vortex. This produces changes in the circulation around the airfoil, energization of the boundary layer, modifications on the three dimensional characteristics of the flow and a channeling of the incident flow, in order to generate higher circulation and then lift force. For those reasons, in order to obtain the desired effect, vortex generator should be taller than the airfoil boundary layer thickness in the place where they are located.

An improvement of the airfoil performance for a certain flight condition, delay or smoothening the stall condition, or produce an enhancement of the lift or drag forces, are all possible desired effects Ref. [17]. Both devices could be placed on the upper or lower surface of the airfoil permanently or only when they become necessary –retractable option-. Their activation could be manual, during take-off or approaching maneuvers, or automatic when stall condition is reached or during a particular maneuver, when a given angle of attack is reached; all this depending on the device and the desired effects.

It is known that, as the angle of attack is increased, drag and lift grows, despite local detachments, up to stall condition. From this point, the drag was continuously increasing, while the lift diminishes.

Through this work we intend to offer further data about the behavior of an Eppler 387 modified airfoil, with vortex generators placed on its upper surface, for a given free stream condition. The lift and drag coefficients behavior will be studied for different angles of attack with and without vortex generators. Also, different positions of vortex generators with different incident angles will be tested Ref. [18].

In other words, the behavior of an Eppler 387 modified airfoil, with vortex generators for a given turbulence and a given Reynolds number, was experimentally studied into the wind tunnel.

## 2 METHODOLOGY

The present work was performed in the following steps:

a) Building of the model (airfoil and vortex generators).
b) Characterization of the turbulence into the wind tunnel.
c) Performing of the wind tunnel experiments.
d) Data analysis.

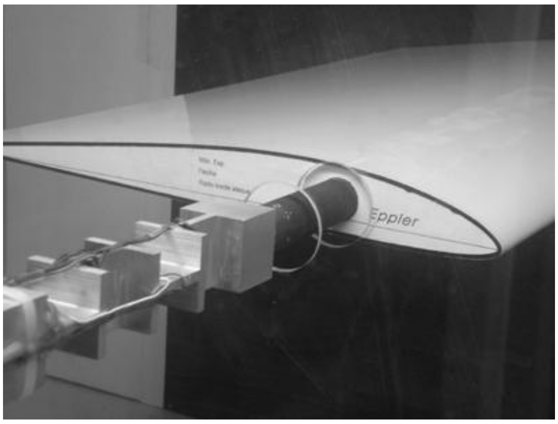


Figure 1: Test experiments of the airfoil into the wind tunnel.

The tested model consists of a 42cm chord and 80cm span wing with an Eppler 387 Fig. (1) modified airfoil Ref. [19] added with triangular vortex generators Fig. (2). The vortex generators are 40mm long, 10mm tall and 0.5mm thick.

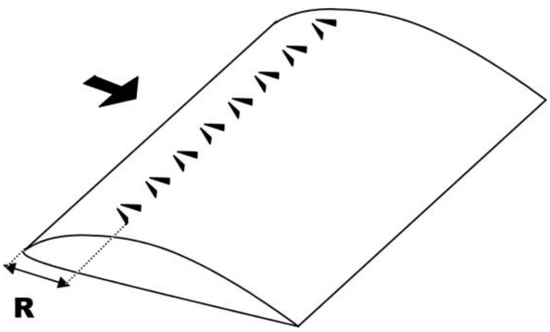


Figure 2: Vortex generators configuration (R=vortex generators location, from the leading edge of the airfoil at 10% to 20% of the chord).

The wind tunnel test section is 7.5m long, 1.4m wide and 1m tall Ref. [20]. Turbulent flow characterization was made by a hot wire constant temperature anemometer. Fig. (3) Ref. [21].

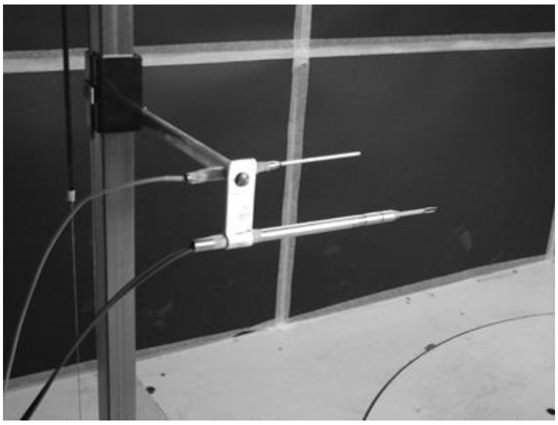

Figure 3: Turbulent flow velocities measurement.

A two component aerodynamic balance with a double load cells Wheatstone bridge was used. The signal was acquired with signal conditioners and Vishay series 2310 amplifiers, connected to a PC Ref. [22].

In order to produce, as close as possible, a two dimensional flow configuration over the wing model, two panels as end plates (Fig. (4)) were located at both sides of the model during the test Ref. [23]. The trailing edge of such panels could be rotate around its longitudinal axe in order to achieve the smallest boundary layer thickness over them. One of the extremes of aerodynamic balance was fixed to the model while the other extreme was fixed to the wind tunnel wall Ref. [24] [25].

Once the desired turbulence characteristics were established and the incoming flow velocity fixed, according to the desired Reynolds number, the test consisted in measuring the lift and drag forces for each given angle of attack Ref. [26]. The previous sequence was repeated for the wing without any device and then for the wing with the vortex generators placed at 10% and 20% of the chord length from the leading edge, at an incident angle of 0º, 10º and 20º from the incoming flow direction.

During the test, temperature, wind velocity, vertical and horizontal loads were measured for different angles of attack Ref. [25]. Loads were acquired at a frequency of 500Hz. A wind tunnel correction was also performed Ref. [27]. All the tests were made at a Reynolds number of 300000.

The aerodynamic coefficients were calculated from the vertical and horizontal forces measured by the balance Ref. [28]. Their values were temperature-corrected and with these data, the three airfoil characteristic curves, lift coefficient vs. angle of attack, drag coefficient vs. lift coefficient and efficiency vs. angle of attack were elaborated Ref. [29].

Figure 4: Rear view of the model and panels into the test section.

## 3 RESULTS

The experiments were carried out for a determined free stream turbulent flow, characterized for its mean and fluctuating velocity components, turbulence spatial and temporal scales. With all of these variables we characterized the flow Ref. [30].

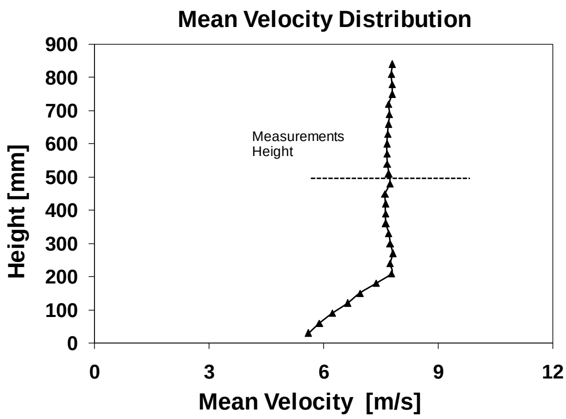


Figure: 5 Mean velocity distribution

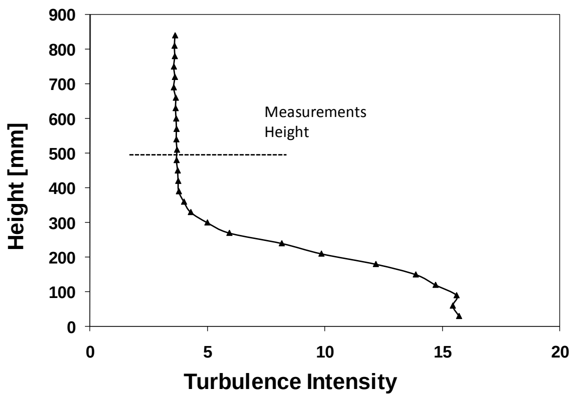


Figure 6: Turbulence intensity distribution

In Fig. (5) we show the free stream mean velocities vertical distribution. The free stream mean flow velocity at the airfoil position height was 7.7m/sec.

In Fig. (6), the turbulence intensity distribution can be observed. At the airfoil´s height level its value is 3.7%. Table 1 shows the calculated values of turbulence intensity for horizontal and vertical component (u and v) at the reference height.

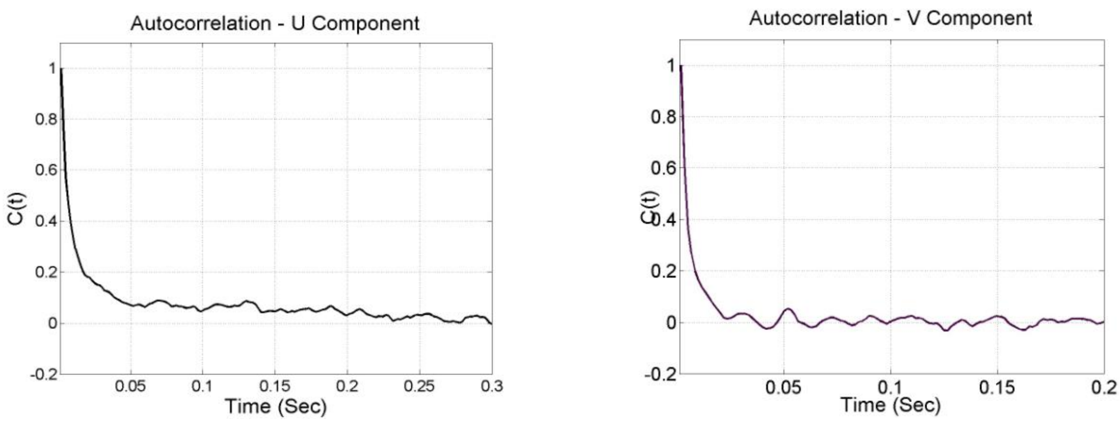


Figure 7: Autocorrelation coefficients

Fig. (7) shows the graphics of autocorrelation coefficients for both u and v components. The temporal scale values obtained are shown in Table 2. We assumed the validity of frozen flow Taylor´s theory, and the values of spatial scales are shown in Table 3.

| Mean Velocity (u component) [m/sec] | Turbulent Intensity (u component) [%] | Mean Velocity (v component) [m/sec] | Turbulent Intensity (v component) [%] |
|---|---|---|---|
| 7,709 | 3,691 | 0,422 | 1,608 |

Table 1: Mean Velocities and Turbulent Intensities (u and v components)

| Temporal Scale u [sec] | Temporal Scale v [sec] |
|---|---|
| 0.0092 | 0.00496 |

Table 2: Turbulent temporal scales

| Spatial Scale U [m] | Spatial Scale V [m] |
|---|---|
| 0.07092 | 0.00209 |

Table 3: Turbulent Spatial Scales

Summarizing,

Incoming flow data:

The mean longitudinal velocity (U) is 7.7 m/sec. The vertical mean velocity (V) is 0.42 m/sec. The turbulence intensity of the u and v components are 3.69% and 1.61% respectively.

Using the frozen flow theory and taking the time scales with the exponential decay criterion in the autocorrelation curve we obtain a time scale for the u component of 0.0092 sec, and for the v component of 0.00496 sec. Indeed, the spatial scales obtained for the u component and v components are 0.07092 m and 0.00209 m respectively.

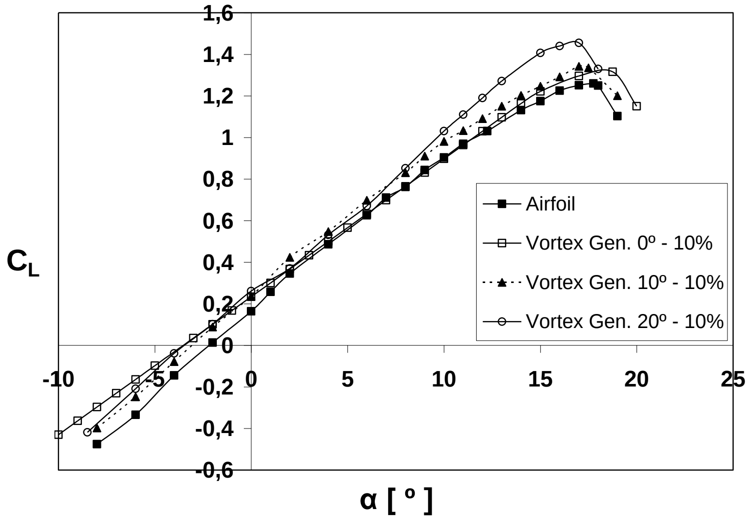


Figure 8: Plots of lift coefficient versus angle of attack (vortex generators at 10% from LE.)

Fig. (8) shows the lift coefficient vs. angle of attack for the wing without any devices, and for the vortex generators placed at 10% of the chord from the leading edge (LE). Practically, no variation in the slope is produced by the vortex generators. A variation in the zero lift angle of attack is detected. However, a change in the maximum lift coefficient is observed. As the vortex generators incidence angle increases, the $C_{Lmax}$ value increases reaching the maximum value corresponding to a vortex generator angle of incidence of 20º, placed on the upper surface of the airfoil.

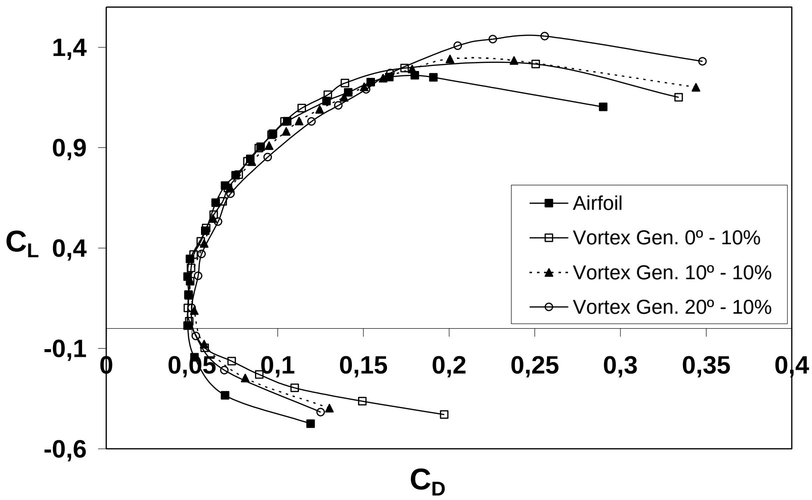


Figure 9: Plots of drag coefficient versus lift coefficient (vortex generators at 10% from LE.)

Fig. (9) shows the drag coefficient versus the lift coefficient. No important drag or $C_{Do}$ variations are observed.

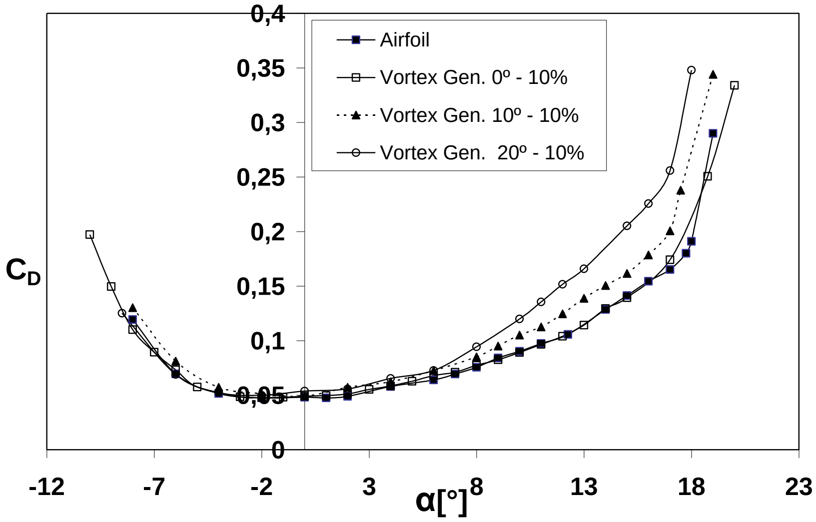


Figure 10: Plots of drag coefficient versus angle of attack (vortex generators at 10% from LE.)

Drag coefficient variation with the angle of attack is shown in Fig. (10). The distance between such curves increase with the angle of attack. As expected, at high angles of attack, the drag coefficient increases for the vortex generators with the greatest incidence angles.

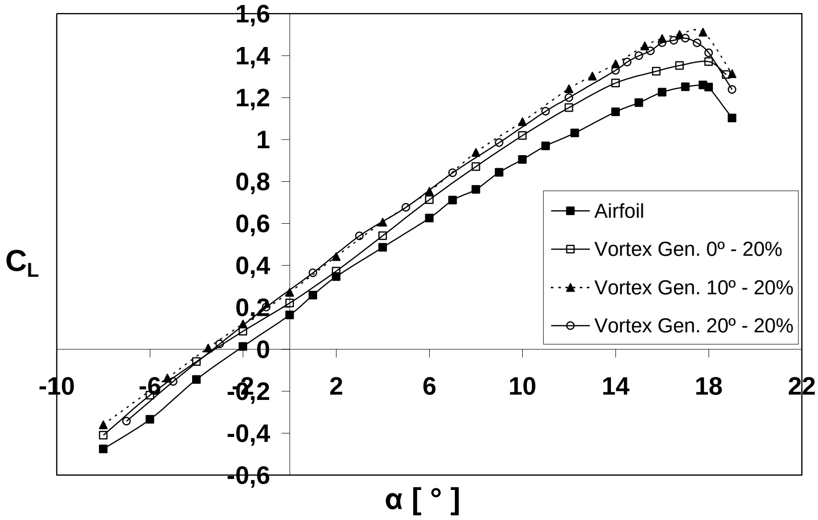


Figure 11: Plots of lift coefficient vs. angle of attack (vortex generators at 20% from LE.)

Fig. (11) shows the lift coefficient vs. angle of attack corresponding to the vortex generators placed at 20% of the chord length from the leading edge. No change is observed in the curves slopes; however, the zero lift angle of attack and the $C_{Lmax}$ vary, repeating the tendency observed for the vortex generators at 10% the chord. In other words, the $C_{Lmax}$ increases as the incidence angle of the vortex generators increases.

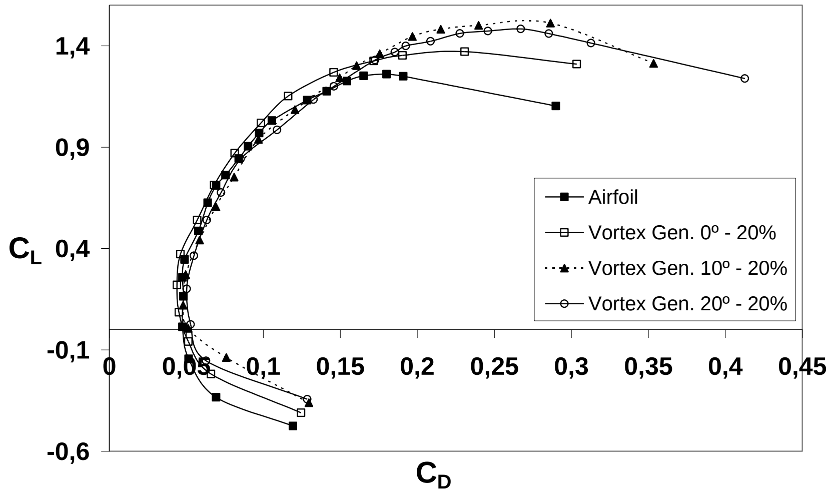


Figure 12: Plots of drag coefficient versus lift coefficient (vortex generators at 20% from LE.)

In the polar curve corresponding to the 20% chord position (Fig. (12)), no important difference can be appreciated in the lift and $C_{Do}$ values. The lowest drag is observed for the vortex generator placed at 20% the chord with an incident angle of 0º.

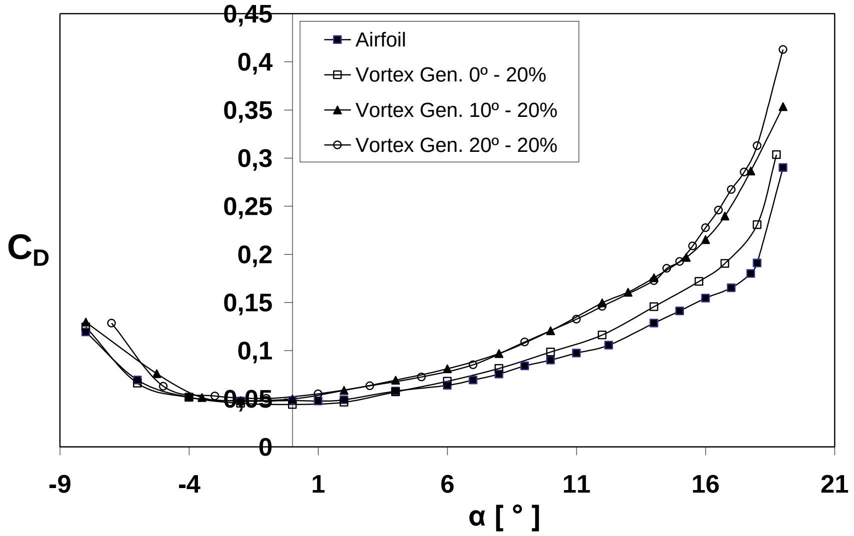


Figure 13: Plots of drag coefficient versus angle of attack (vortex generators at 20% from LE.)

Fig. (13) shows a similar behavior of the vortex generators placed at 20% of the chord from LE in relation to those placed at 10% of the chord. As the angle of attack increases the drag is higher in the airfoil with devices at a higher angle of attack.

| Device | $\alpha$ | $C_L$ max | $C_{do}$ |
|---|---|---|---|
| Airfoil | 17.75º | 1.26 | 0.0475 |
| Vortex Gen. 0º -10% | 18.75º | 1.31 | 0.0485 |
| Vortex Gen. 10º-10% | 17º | 1.34 | 0.0581 |
| Vortex Gen. 20º-10% | 17º | 1.45 | 0.0501 |
| Vortex Gen. 0º -20% | 18º | 1.37 | 0.0481 |
| Vortex Gen. 10º-20% | 17.75º | 1.51 | 0.0518 |
| Vortex Gen. 20º-20% | 17º | 1.48 | 0.0531 |

Table 4: Comparative values for the different devices

Table 4 shows the results of the airfoil without any devices and the airfoil with the vortex generators. For each case, the values of $C_{Lmax}$ and its corresponding angle of attack, and $C_{Do}$ are shown. It can be observed no major change in the stall angles.

From such Table we could deduce that using a vortex generator with 0º of incidence placed at 10% of the chord from the leading edge, the value of $C_{Lmax}$ increases 4%. Even more, if the vortex generator is placed at an angle of incidence of 10º, $C_{Lmax}$ increases 6.3%, and if it is placed at an angle of 20º, $C_{Lmax}$ increases 15%.

For the cases with the vortex generators placed 20% the chord, $C_{Lmax}$ increases 8.7% for 0º incidence, 19.8% for 10º, and 17.4% for 20º.

| Device | E max | $\alpha$ (E max) | $\alpha$ ($C_L$ = 0) | $C_L$ ($\alpha$ = 0) |
|---|---|---|---|---|
| Airfoil | 10.24 | 7º | -2 | 0.163 |
| Vortex Gen. 0º -10% | 10.08 | 10º | -3.5 | 0.236 |
| Vortex Gen. 10º-10% | 9.76 | 8º | -3.25 | 0.236 |
| Vortex Gen. 20º-10% | 9.23 | 6º | -3.5 | 0.261 |
| Vortex Gen. 0º -20% | 10.68 | 8º | -3.25 | 0.221 |
| Vortex Gen. 10º-20% | 9.68 | 8º | -3.5 | 0.271 |
| Vortex Gen. 20º-20% | 9.86 | 7º | -3.25 | 0.269 |

Table 5: Comparative values for the different devices

Table 5 shows the comparative values for the different devices describing the maximum efficiency and their corresponding angle of attack, the zero lift angle of attack for the airfoil and the value of the $C_L$ for zero angle of attack.

No major changes can be observed in the efficiency of the devices. However, some differences are observed in the angles at which the changes appear. The airfoil with a turbulator at 20% and 0° offers a higher efficiency than the airfoil with no devices.

As it was observed in the results obtained from the performed experiments, these vortex generator devices placed on airfoils obtain an increment in the value of the $C_{Lmáx}$, with regard to the case of the airfoil without devices. In addition, a difference is observed in the case of an increment in the vortex generator angle of attack ($\alpha$) respect to the free stream**.**

The results indicate that the vortex generators produce a flow around and downstream from them, with the same characteristic that a delta wing generates, provoking a disorder in the flow inside and outside of the boundary layer, which in this position is supposed to be totally turbulent.

It is observed that the $C_{Lmáx}$ increases but the stall angle of attack diminishes very little or is kept constant. It is also observed that in all the cases the stall is smooth. The curve increases a bit its slope in the quasi linear zone.

It is possible that the lift increment is due to an increment in the circulation around the airfoil, generated by a favorable pressure gradient that stabilizes the boundary layer on the upper surface of the airfoil. Every vortex generator produces a spiral vortex that interacts with the boundary layer and modifies the configuration of the flow behind the devices. This implies that the incidental flow sees an airfoil of larger thickness, which would explain the lift increment.

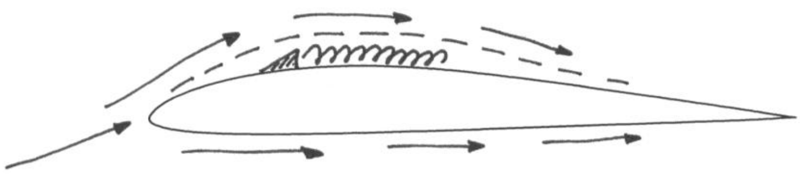

Figure 14: Flow around an airfoil with vortex generator

The drag coefficient is kept almost constant for low angles of attack, with a lower value for the case without the device. As the angle of attack is increased the $C_D$ increases, and this behavior become more important for the stall zone of the airfoil. This increment results from the interaction between the vortex generated and the thickness of the boundary layer.

In general, a spiral vortex generated with delta wings, similar to the used in these vortex generators, has certain stability determined, among other things, by the Reynolds number and the intensity of the turbulence. Vortex explodes more rapidly with the increment of the flow turbulent intensity. This brings that on the airfoil, the longer the vortex lasts, the more flow mixes with the boundary layer, and therefore the outer flow will see an airfoil with major thickness and major curvature (provided that the devices are in the upper surface), consequently with major circulation, $C_L$ obtained is major. On the other hand, when the vortex explodes it generates a flow with minor energy, which produces less mixture, and the external flow will see an airfoil thinner, therefore there will be less circulation and less $C_L$.

## 4 CONCLUSIONS

Higher values of $C_{Lmax}$ can be obtained using different configurations of vortex generator devices on wing airfoils. Different values of $C_{Lmax}$ are observed for vortex generators placed at different angles of attack respect to the free stream flow direction Ref. [31]. As drag and lift change simultaneously, no important change in the efficiency is observed.

The results indicate that the vortex generators must generate a flow in their surroundings similar to that produced by a Delta wing, provoking a disorder in the boundary layer, in such a way that the $C_{Lmax}$ results increased, at the same time that the stall angle of attack decreases a minimum or stays constant. It is observed, as well, that in all the cases the stall is smooth Ref. [32]. The curve's slope increases a little or it is moved to the left as if a fowler flap were acting.

The detected lift increment is connected with a circulation increment, which generate a favorable pressure gradient. Each turbulator generate helicoidally vortices which interact with the boundary layer, modifying the flow wake behind the turbulators. This flow pattern is responsible of an “apparent” increment of the airfoil width and, consequently, of the lift increment.

The fact that the drag coefficient has almost no changes could be caused by the interaction between the generated vortices and the boundary layer. This effect is similar to the case of turbulators, which sizes are similar to the boundary layer thickness. It is well known, that as higher turbulent the boundary layer is, better could it face an adverse pressure gradient and, in that situation, delay the stall for a given angle of attack, in comparison with the same airfoil submitted to a laminar free stream. At that Reynolds number, we could assume that the mix of the generated vortices with the boundary layer, promotes an increase of the turbulence intensity inside it. The effect is similar to the increment of the surface roughness of the airfoil.

The main contribution to drag is the form drag or pressures one, which becomes increasingly important as the angle of attack increase. This drag grows significantly from the separation. McMasters and Henderson Ref. [33] showed that an airfoil with roughness has major efficiency that a smooth one up to Re = 500.000, and for greater Re the situation reverts.

It happens that, when the adverse pressures gradient is not large, the transition and the reattach of the flow can occur after a laminar separation (laminar bubble separation) and, in consequence, the subsequent turbulent boundary layer will be more resistant to the separation. Thus, this leads to a reasonable justification of anticipating the detachment across provoking an early transition to laminar-turbulent Ref. [34].

Further experiments and computational simulations should be performed with different vortex generators in order to study their effect. It is also important to analyze what kind of vortices is being generated and which is their effect on the airfoil, either on its circulation and/or on its boundary layer.

The work should continue repeating the tests for different turbulent configurations of the incoming flow.

Therefore, we can conclude that the vortex generators always increase the $C_{L.}$ The airfoil alone always has minor drag that any of the cases studied with vortex generators devices. We don’t observe evidences of hysteresis phenomena even evidences of laminar separation. The boundary layer on the airfoil must be totally turbulent.

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