EXPERIMENTAL STUDY OF THE INFLUENCE OF VORTEX GENERATORS ON AIRFOILS FOR WIND TURBINES

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ABSTRACT

An experimental analysis was made to study the influence of vortex generators on the aerodynamic characteristics of the NACA 63-415, NACA 63-215 and NACA 63-430 airfoils, commonly applied in the design of wind turbines blades. In order to do so, low-speed wind tunnel experiments of the airfoil models were conducted at the Aerodynamic Laboratory of the Engineering School of São Carlos, of the University of São Paulo. Tests were made to measure forces, moments and pressure distribution over the airfoils in each situation, i.e., with and without the vortex generators, at Reynolds number of 320,000. Thus, three different sizes of vortex generators were tested; they were placed at 10% of the models chord from the leading edge, with their heights in the same order of magnitude of the estimated height of the local boundary layer. The results showed an improve in the maximum lift coefficient for the NACA 63-215 and NACA 63-415, moreover, the lift to drag ratio was also increased for the NACA 63-215 at angles of attack close to stall. On the other hand, the airfoil NACA 63-430 didn't have any improvement, in which the slope of the lift curve was reduced and the drag was increased.

Keywords: Aerodynamics, Boundary Layer Control, Vortex Generators, Wind Energy, Wind Turbines Airfoils.

1 INTRODUCTION

Wind energy is one of the most promising sources of renewable energy, and has been widely employed in countries of Europe, the United States and China, and more recently in emerging countries like Brazil, which has a great production potential of this kind of energy. Amarante *et al.* [1] concluded that Brazil could produce 143 GW with wind energy. Thus, in order to generate this energy, it must have efficient wind turbines.

The efficiency of a wind turbine has a maximum called Betz limit, which states that no more than 59.3% of the available energy of the wind flow can be collected. In this way, a wind turbine design seeks to achieve efficiency of energy extraction as close as possible of this limit. Therefore, a simple way of improving the rated power is by using vortex generators in the wind turbine blades. An investigation of the influence of vortex generators on the performance of a wind turbine showed that without vortex generators, the maximum power production was 800 kW and with vortex generators reached 1.0 MW [2].

Vortex generators are small vanes mounted perpendicular to the surface of the blades with an angle to the incoming flow. These devices may have several shapes, but this paper only studied the rectangular shape. The vanes can be arranged in pairs in order to create contra rotating vortices, as shown in Figure 1, or parallel to each other providing co-rotating vortices. According to Gad-el-Hak [3] contra rotating configurations could imply in regions with excessive vorticity over the airfoil surface, however co-rotating configurations with vortex generators too close may cause mutual vorticity cancellation, therefore, spacing is critical in this case. This study had no intention to investigate the differences of each configuration, thus it was decided to use only contra rotating configuration.

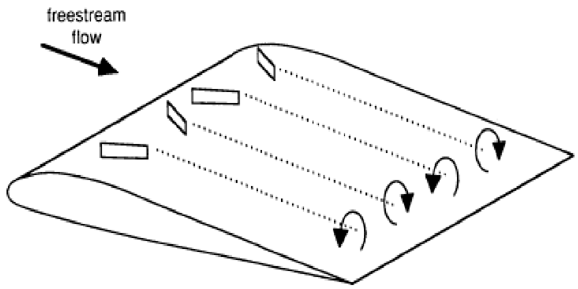


Figure 1: contra rotating vortex generator configuration.

The purpose of these passive devices is to transfer momentum from de incoming flow to the airfoil surface, making the flow more resistant to adverse pressure gradients, which tend to separate the boundary layer, hence, the airfoil could operate at high angles of attack without occurring stall. Nevertheless, it should be noted that vortex generators imply in excessive drag at conditions in which boundary layer detachment is not imminent, however this effect is small compared to the gains in performance under other operating conditions [4]. One way to avoid this problem is by retracting the devices when they are not needed, but then they would constitute active devices, which requires power and mechanical apparatus to function. Moreover, one of the most important features of this kind of device is that it is a passive type, i.e., it does not need power to operate, unlike other forms of flow control such as blowing and suction, which could be as effective as vortex generators by delaying boundary layer separation, but necessarily consume some of the power generated and increase the maintenance costs, since the holes in which the air flow passes must be periodically washed in order to avoid dirt from obstructing the ducts.

The aerodynamics of wind turbines could be based on the Momentum Theory and the Blade Element Theory, which can be found in Manwell [5] and Leishman [6], and assume that there is no aerodynamic interaction between the elements and the forces on the blades are determined solely by the lift and drag characteristics of the airfoil shape of the blades. Consequently, the bidimensional airfoil coefficients are applied in the equations that describe the mechanics of wind turbines blades. Yet, when the angles of attack become large and flow separates, these hypotheses are no longer valid, and the low momentum fluid in the separated boundary layer region is exposed to centrifugal and Coriolis forces yielding strong three dimensional effects [7], thus, developing radial flow. If vortex generators are used, the boundary layer could be kept attached to the blades holding the assumption of bidimensional flow, thereby the Blade Element Theory remains valid.

An estimation of the local boundary layer thickness was necessary in order to design the vortex generators height; therefore, using the rate of growth of the laminar boundary layer, since the Reynolds number is low, on a flat plate, it was possible to make an inaccurate but reasonable approximation.

Hence, it is important to understand the effects of vortex generators on the bidimensional aerodynamic characteristics of the airfoils which constitute the wind turbine blades. Thereby, wind tunnel tests were made with models of the airfoils NACA 63-215, NACA 63-415 and NACA 63-430, with and without vortex generators. Forces and moments were measured in order to obtain the curves of lift, drag and moment coefficients, and also the distribution of pressure coefficient (cp), which will only be presented those curves that show the influences of vortex generators on the boundary layer control. The airfoils are shown in Figure 2, Figure 3 and Figure 4. It is important to remark that the NACA 63-215 and NACA 63-415 are 15% thick and they are only different in camber with 1.1% for the NACA 63-215 and 2.2% for the NACA 63-415. The airfoil NACA 63-430 is 30% thick and has 1.7% in camber.

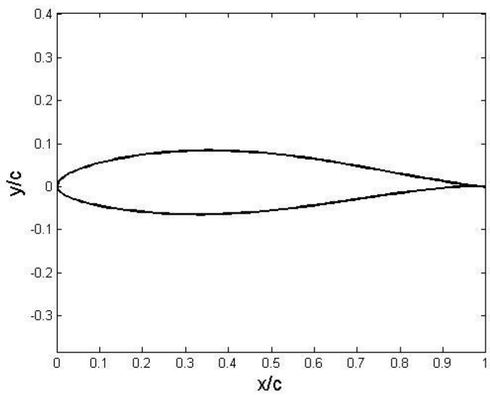


Figure 2: airfoil NACA 63-215

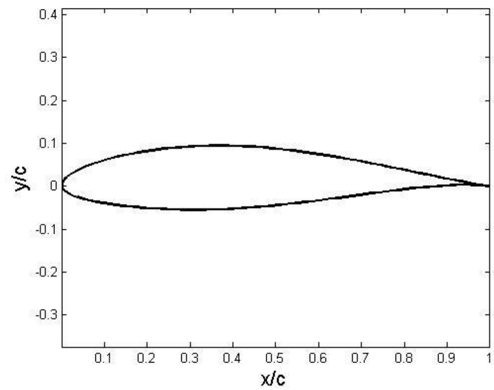


Figure 3: airfoil NACA 63-415

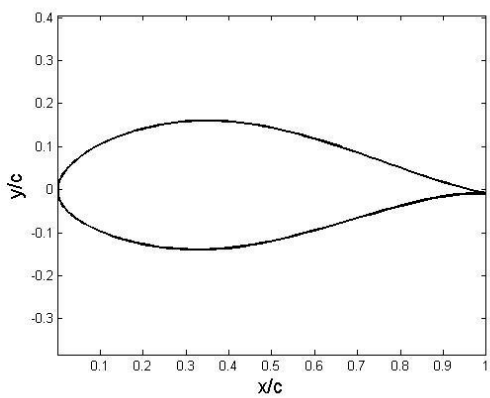


Figure 4: airfoil NACA 63-430

2 EXPERIMENTAL CONSIDERATIONS

The low-speed wind tunnel of the Aerodynamic Laboratory of the Engineering School of São Carlos, of the University of São Paulo is an open return type. The rectangular test section is nominally 460 x 460 mm in cross section and 1200 mm long. The test section reaches speeds up to 30 m/s, however, every test was conducted at 20 m/s, resulting in Reynolds number of 320,000 based on airfoil chord. In order to ensure good flow quality, the inlet has a honeycomb.

The airfoil models had 250 mm chord and 450 mm span, thus leaving a gap of 5.0 mm with the wind tunnel walls. Each model consisted of 8 ribs of medium density fiberboard (MDF) 6.0 mm thick and the surface was made from crystal PVC plate 0.7 mm thick. A stainless steel bar located at one quarter chord held all together. Pressure measurements were made through 42 pressure taps with 1.0 mm diameter located at the airfoils mid span, in an inclined configuration. Figure 5 shows an airfoil model.

Figure 5: airfoil model.

Forces were measured in the stainless steel bar by an external aerodynamic balance with three degrees of freedom, which permits rotation of the airfoil model. The pressure taps were connected to a SCANIVALVE that allow readings of ±1.0 psi. A Pitot tube at the cross section inlet measured the total and static pressure of the incoming flow.

The vortex generators were made of the same material of the airfoil surface, i.e., crystal PVC plate 0.7 mm thick. These were small rectangular vanes with their length four times the height, located at 10% of the models chord from the leading edge, or 25 mm. The yaw angle was 20° and the spacing parameters of Figure 6, according to Table 1.

Table 1: vortex generators spacing parameters.

Spacing Parameters (mm)	
d	**P**
25	37.5

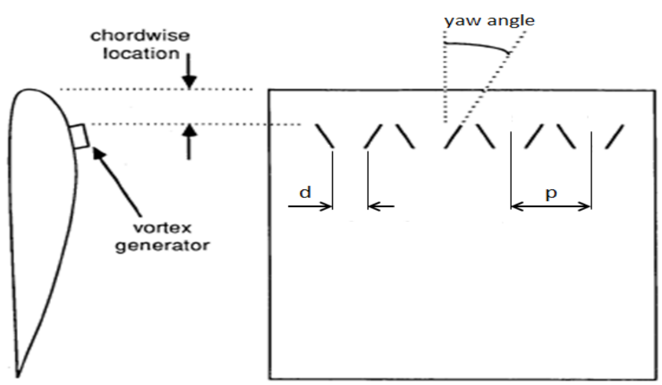


Figure 6: vortex generators spacing.

The estimative of the boundary layer thickness at 10% chord from the leading edge was made according to Houghton [8], in which was assumed laminar boundary layer because of the low Reynolds number of the tests. The local Reynolds number is given in Eq. (1) and the rate of growth in Eq. (2).

$$Re_x = \frac{Vx}{\nu} \tag{1}$$

$$\frac{t}{x} = \frac{4.64}{\sqrt{Re_x}} \qquad (2)$$

The incoming velocity V was set constant at 20 m/s, the kinematic viscosity ν was assumed 1.56×10^{-5} m^2/s, and for the position of 10% chord, or 25 mm, the local Reynolds number $Re_x = 32000$, which leads to $t = 0.648$ mm. Besides, the height of the vortex generators must be of the same order of magnitude of t. It would be very difficult to produce and guarantee the dimensions of a device of 0.648 mm, so the smallest vortex generator height was 1.5 mm. Also were made devices of 3.0 and 6.0 mm height. All vortex generators (VG) dimensions can be found in Table 2.

Table 2: vortex generators dimensions.

VG Height (H, mm)	VG Length (L, mm)	H/t	L/model chord	H/model chord
1.5	6.0	2.31	0.024	0.006
3.0	12	4.63	0.048	0.012
6.0	24	9.26	0.096	0.024

Wind tunnel corrections such as lift interference, solid blockage and wake blockage were made following ESDU 76028 [9] for closed walls wind tunnel. Furthermore, according to Barlow *et al* [10], almost all wind tunnels with closed throats have a variation in static pressure along the axis of the test section, in this manner, it was measured the difference between the static pressure of the incoming flow through the inlet Pitot tube and the one quarter chord position of the airfoils models, but without the models in the test section. It was discovered an increase of 1.6% in the static pressure, which was included in the corrections.

3 RESULTS AND DISCUSSION

Results of the wind tunnel tests of the airfoils NACA 63-415, NACA 63-215 and NACA 63-430 with each size of vortex generators and also with clean surface, are presented with curves of the lift coefficient (cl), drag coefficient (cd), moment coefficient at one quarter chord (cm1/4) and lift-to-drag ratio (cl/cd), all of them as functions of the angle of attack. Moreover, in order to understand the influence of these devices on the pressure distribution around the airfoils surface, graphics of pressure coefficient (cp) of some of the angles of attack tested are shown.

The vortex generators made a substantial increase in the maximum lift coefficient for this airfoil, from cl_{max} = 1.27 with clean surface to cl_{max} = 1.34 with H/chord = 0.006 and cl_{max} = 1.38 with H/chord = 0.012. Furthermore, there was also an improvement in the lift-to-drag ratio for the case with H/chord = 0.006 due to reduction on cd at angles of atack between 9° and 17°. The case with H/chord = 0.024 did not improve the lift coefficient neither the drag coefficient. The moment coefficient at one quarter chord had a reduction with H/chord = 0.012 and 0.024.

This important features can be explained by the retardation of the boundary layer separation, this phenomenon can be seen in the graphics of cp, in which is possible to notice that the boundary layer is already detached at 13° with clean airfoil surface, while with vortex generators this happens only at 16°. An important effect is the peak of reduced pressure in the position of the vortex generators, i.e., at 10% chord, being strongest for the biggest VG. Furthermore, the VGs eliminated the laminar separation bubble at low angles of atack, by removing the kink, for instance, between 60% to 70% chord at 0° and 45% to 55% at 5°.

The airfoil NACA 63-430 is substantially different from the NACA 63-215 and NACA 63-415 airfoils since it is twice as thick. Therefore, the aerodynamic characteristics should be also different. Evidently, the use of the VGs worsened the lift coefficient at every situation tested; furthermore, it raised the drag coefficient, consequently, the lift-to-drag ratio dropped significantly. Still, the moment coefficient was reduced concurrently to the fall in the cl. Probably, all of this bad features was caused by the positioning of the VGs, it possibly would present better aerodynamic characteristics if those devices were placed more distant from the leading edge, since the suction peak moves close to 10% chord only at high angles of attack in the case with clean surface, being farther from the leading edge at most of the other situations.

Examining the pressure coefficient distributions it is possible to observe that the use of vortex generators at 10% chord is anticipating the boundary layer separation, where it starts at 10° with the VGs and only happens at 17° with the clean surface. Therefore, the use of VGs at 10% chord for thick airfoils like the NACA 63-430 is not recommended, however it should be investigated if placing the vortex generators more distant from the leading edge would improve the aerodynamic performance of the airfoil.

3.1 NACA 63-215

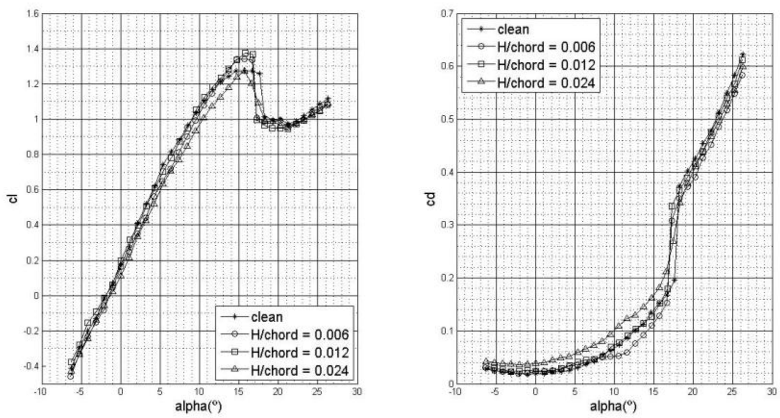


Figure 7: lift and drag coefficients for the airfoil NACA 63-215

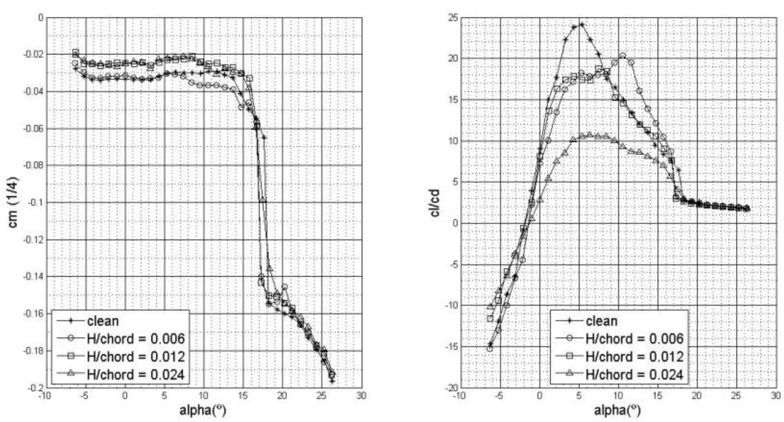


Figure 8: moment coefficient at one quarter chord and lift-to-drag ratio for the airfoil NACA 63-215

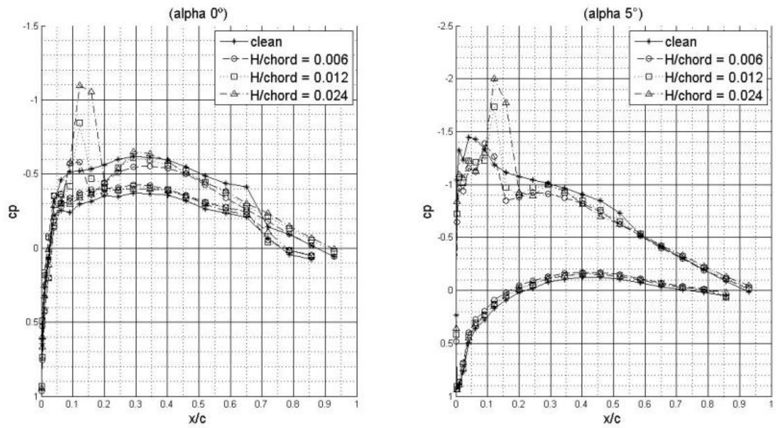


Figure 9: pressure coefficient distribution (cp) for the airfoil NACA 63-215 at 0° and 5°.

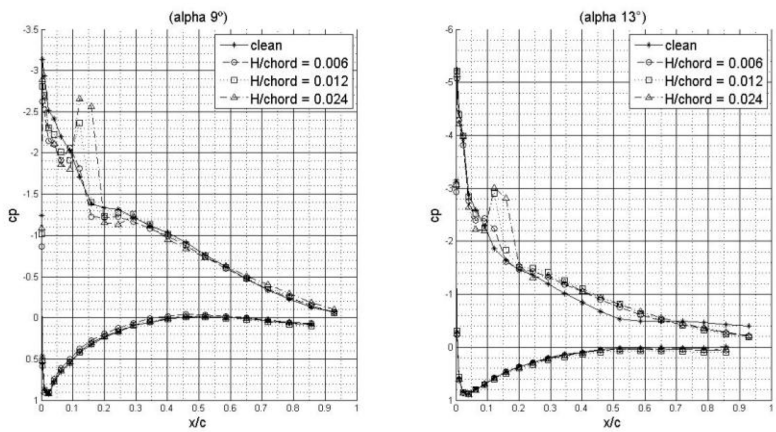


Figure 10: pressure coefficient distribution (cp) for the airfoil NACA 63-215 at 9° and 13°.

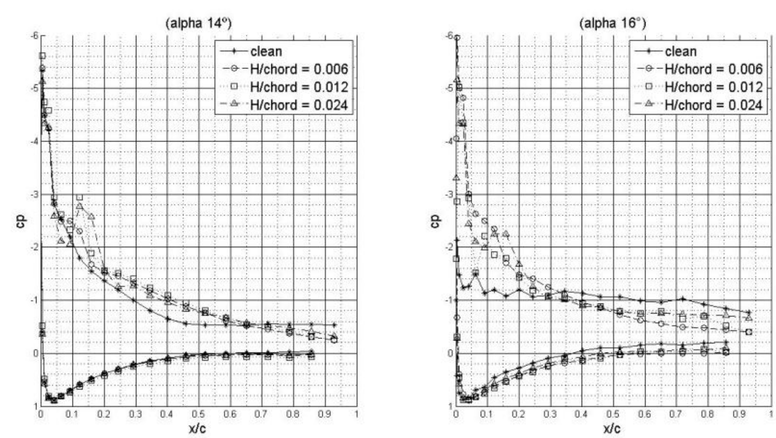


Figure 11: pressure coefficient distribution (cp) for the airfoil NACA 63-215 at 14° and 16°.

3.2 NACA 63-415

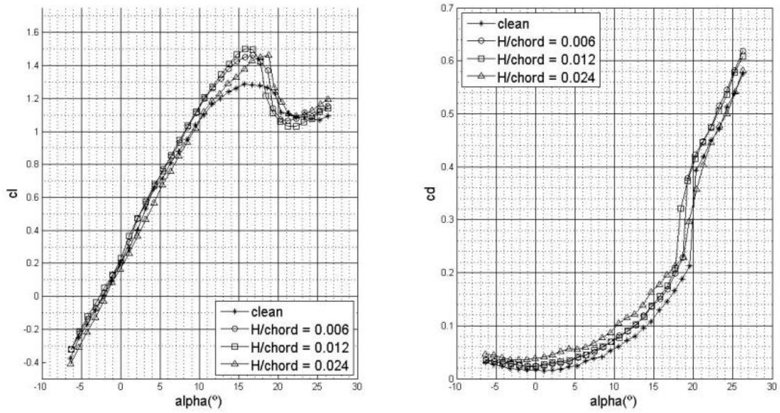


Figure 12: lift and drag coefficients for the airfoil NACA 63-415

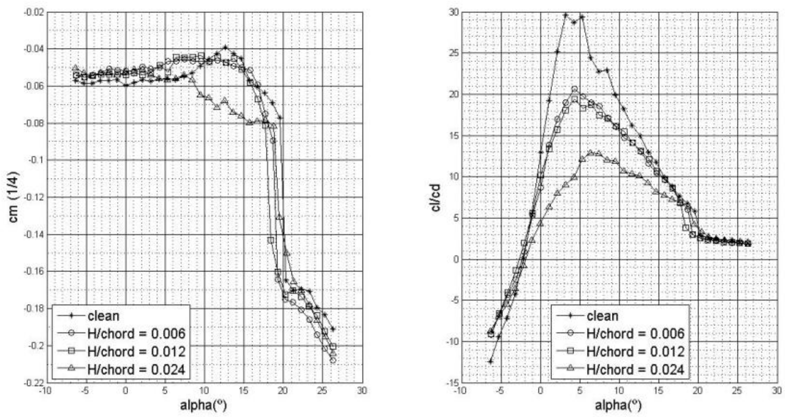


Figure 13: moment coefficient at one quarter chord and lift-to-drag ratio for the airfoil NACA 63-415.

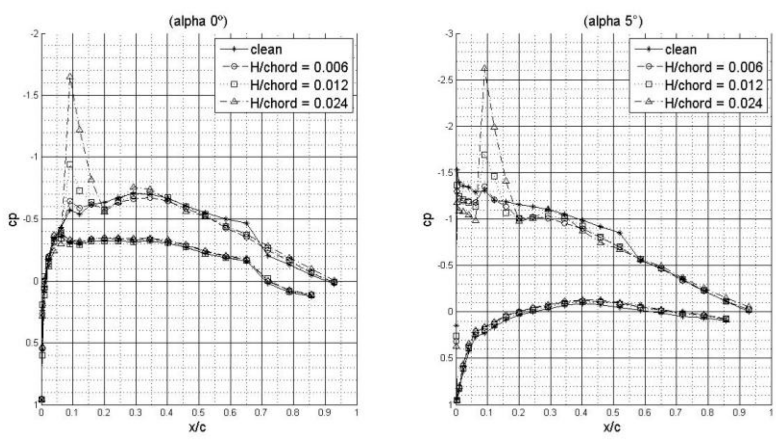


Figure 14: pressure coefficient distribution (cp) for the airfoil NACA 63-415 at 0° and 5°.

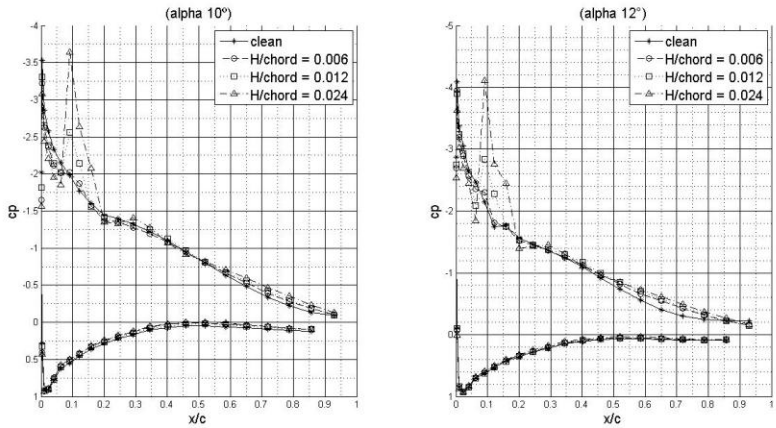


Figure 15: pressure coefficient distribution (cp) for the airfoil NACA 63-415 at 10° and 12°.

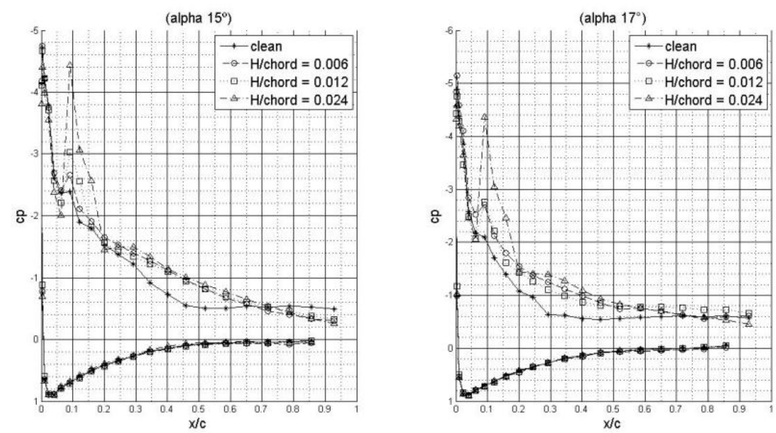


Figure 16: pressure coefficient distribution (cp) for the airfoil NACA 63-415 at 15° and 17°.

3.3 NACA 63-430

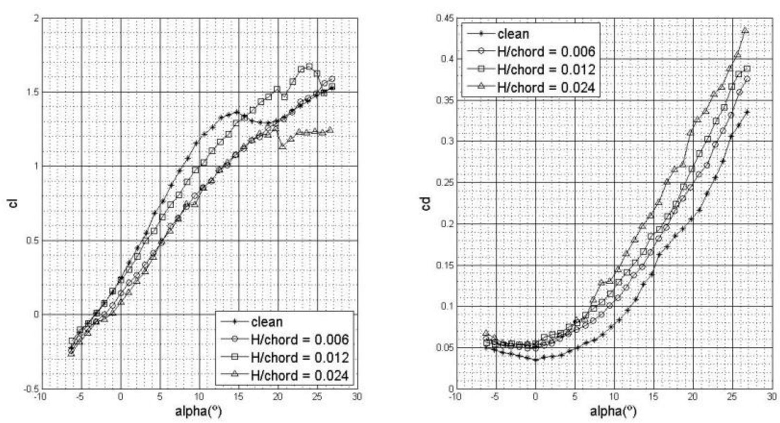
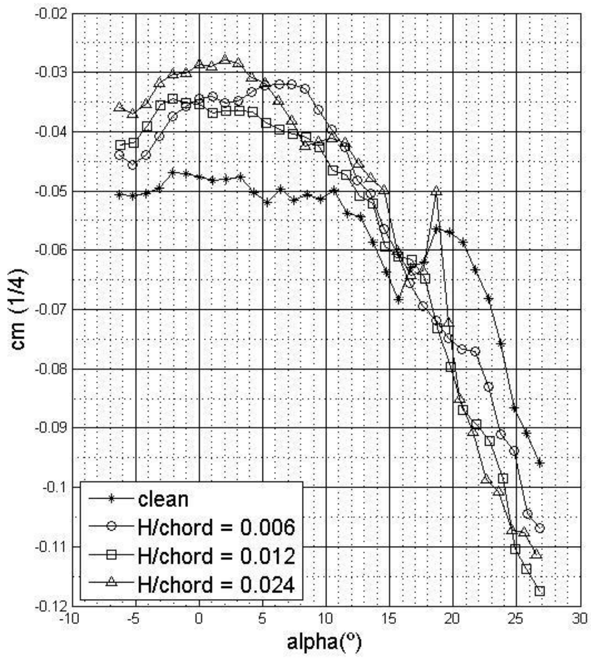


Figure 17: lift and drag coefficients for the airfoil NACA 63-430



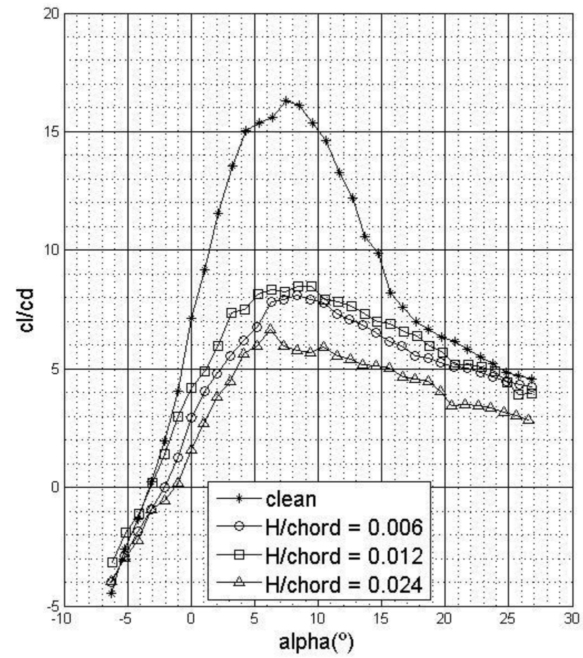
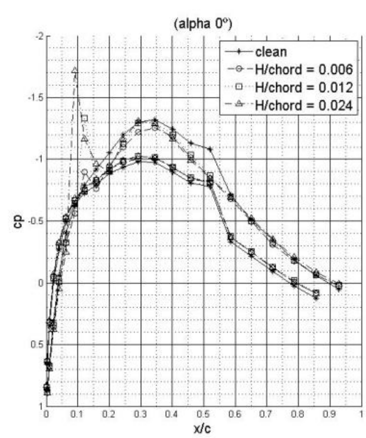


Figure 18: moment coefficient at one quarter chord and lift-to-drag ratio for the airfoil NACA 63-430



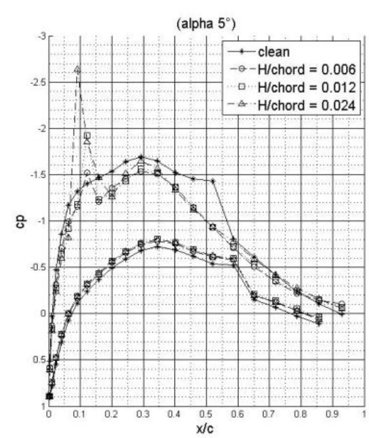


Figure 19: pressure coefficient distribution (cp) for the airfoil NACA 63-430 at 0° and 5°.

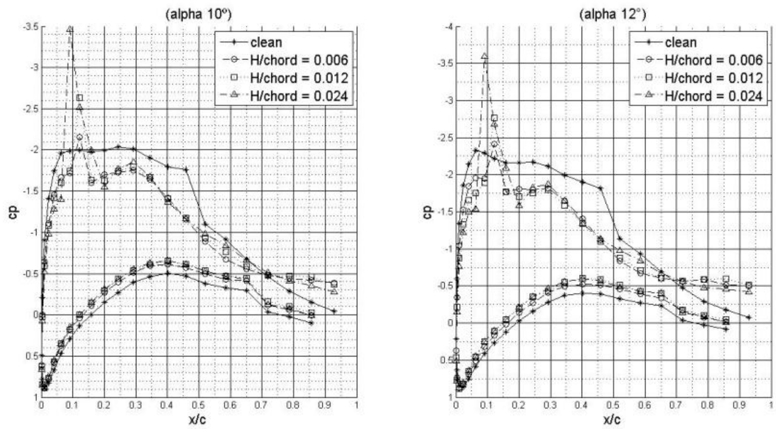


Figure 20: pressure coefficient distribution (cp) for the airfoil NACA 63-430 at 10° and 12°.

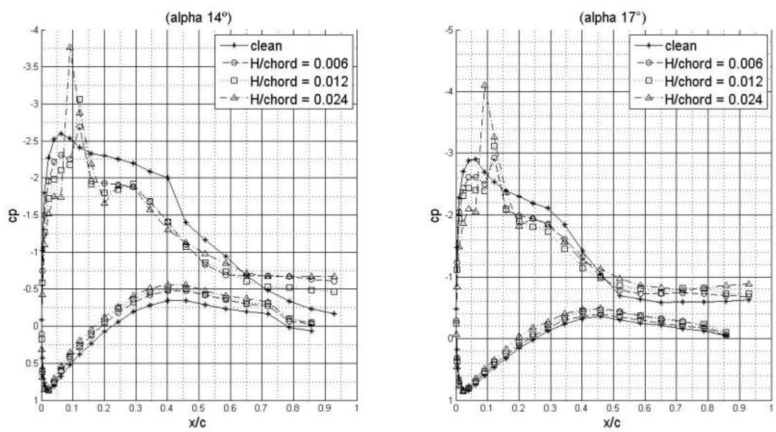


Figure 21: pressure coefficient distribution (cp) for the airfoil NACA 63-430 at 14° and 17°.

4 CONCLUSIONS

The use of vortex generators can considerably improve the aerodynamic characteristics of the NACA 63-215 and NACA 63-415, enhancing the maximum lift coefficient by delaying the boundary layer separation and in some cases reducing the drag coefficient, since while holding the boundary layer attached to the surface, it avoids the sudden increase in pressure drag, which could be bigger than the increase in friction drag due to the additional vorticity created by the VGs, thus, as could be seen for the NACA 63-215, there can be also better features in the lift-to-drag ratio. It was also noted that the smaller the VG the lower would be the increase in drag; nevertheless, there is a limit to how small the VG can be, especially at low Reynolds number. The positioning of the VGs is as well important, once for the NACA 63-430 there was no improvement in the aerodynamic performance, which might be related to the positioning at 10% chord from the leading edge. Further tests on the positioning of the VGs would probably observe better results with thick airfoils if the VGs were placed more distant.

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