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Influence of roughness in protective strips of leading edge for generating wind profiles

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Abstract. *The aim of this research is to study the influence of a leading edge protection tape at the aerodynamic characteristics of the airfoils DU93-W210, FFA-W3-211 and NACA 63415, widely used in wind turbines blades. This tape protects the blades leading edge from airborne particles, such as sand and insects and yet eases the blades maintenance.*
Computer simulations were carried out using software XFLR5.Four models were built with MDF ribs and PVC skin for 2D tests. The experiments were carried out in a wind tunnel with section of 45cm x 45cm and Reynolds number 315000. The experiments consisted from one test with a clean surface to be used as reference and variations in the placement of the tape the chord wise. Then, for each respective setting, was varied surface roughness using different grain sizes of sand. In order to obtain the data, the forces were getting, as well the pressure coefficients were taken through the a SCANIVALVE system. The collected data was used to plot the curves of aerodynamic drag, lift, pitching moment and efficiency for each condition, in order to compare them and infer the effects of the tape and roughness on the aerodynamics characteristics of the airfoils.

Keywords: *Wind turbine airfoils, wind energy, tapes leading edge.*

1 INTRODUCTION

In the past few years, it has been noted the necessity of developing alternative ways of generating energy. The traditional sources, which by now have been massively used, reveal disadvantages which make necessary the development of new technologies in energy matrixes.

The fossil fuels, apart from having finite reserves, release pollutant gases in the atmosphere, evoking a latent ambient awareness. Therefore, their utilization for generating electric energy in thermoelectric plants is not very advantageous. On the other hand, the hydroelectric plants flood large areas, modify the geography of a region and change the course of rivers, apart from requiring big quantities of investments for their implementation. The nuclear plants, in their turn, have the great problem of radioactive waste, which, for having a very large half-life, needs a monitoring for a long time.

In this context, the development of renewable resources of energy becomes extremely important. Among them, the eolic energy has a prominent place, due to its great energetic potential, since the wind is everywhere in the globe and, in some areas, with high energetic density (Warsop, 2006)

Therefore, it is important that the eolic turbines have a growing efficiency, for that a great part of the kinetic energy existent in the wind be converted to electric energy. In this aspect, the aerodynamic study of the turbines' blades is excessively necessary. Particularly, the control of the separation of the boundary layer is a focus to be studied, because this phenomenon involves significant loss of energy, increases the instability of the flow and limits the performance of the airfoils. (Warsop, 2006)

Another important focus of the study is the maintenance of the eolic turbines' blades, because the aerodynamic and structural characteristics of the blades must be kept, because they are essential to the economic optimization of the eolic energy. In this sense, the study of the erosion of the blades' leading edges is necessary, because the winds, depending on the locality, can carry large quantities of sand, erosive particles which can damage the leading edge, causing an increment of rugosity, which damages the aerodynamic performance (Fei, Yong, & Jihua, 2010).

So, this research project was aimed at the study of the effects of the erosion and the incrustation of dirt upon the leading edge of eolic generators' blades, using protective strips against erosion already used commercially. So, it was

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able to understand what is the influence of these strips on the aerodynamic efficiency of blades and propose ways to try to improve or to minimize their effects upon them.

2 LITERATURE REVIEW

2.1 Eolic generator and Brazillian installable potential

The re-emergence of the wind as a significant source of energy is one of the most significant developments of the 20th century. The advent of the steam turbine, followed by the appearance of new technologies to convert fossil fuels into utile energy, seemed to have set aside the wind's role in generating energy (Manwell, 2002). However, in the end of this century, this situation started to revert, mainly because of the possibility of shortage of non-renewable fuels, and still because of the perception of the great eolic potential of many countries. In addition to this, there was, in many countries, a great politic will for the development of renewable energies, in which the eolic energy fits, be it in the research financing or in the government subsidy given to the eolic energy producers (Manwell, 2002).

The eolic generator is, in short, a machine that picks up a part of the kinetic energy of the wind that passes through the area comprised by the rotor, transforming it into rotation energy of the rotor itself and finally, through an electric generator, converting it to electric energy, in which the final power is function of the cube of the speed of the wind acting in the generator. In Brazil, there is a great potential for producing eolic energy. If we consider winds over 6 m/s and medium curves of performance of eolic turbines existent in the market in 2001, in the northeast region, where this potential is bigger, the capacity of producing electric energy through eolic generators is about 490,21 GW. Speaking of the whole country, there is an accumulated potential of generating 1334,78 GW of power (Amarante, Brower, Zack, & Sá, 2001).

2.2 Erosion and the effects of rugosity on eolic generator's blade

In operation, the eolic generators' blades are subject to collision with suspended particles in the air and insects, which can incrust over the blades' leading edges, or still, cause the erosion of them. All these factors can affect severely their aerodynamic performance, because of the increase of rugosity in the blades' surface. In this sense, some works have already reported the influence of rugosity on eolic generators' blades.

Nascimento (Nascimento, 1998) tested, in wind tunnel, a model of a eolic generator with airfoils of the family W1 of FFA and noted that for the rugosities put until approximately 4% of the chord, the power generated by the turbine fell 25% at average. Yet if the rugosity was put in a broad interval throughout the chord, the researcher has observed that the loss increased until 46% and, for greater rugosities, it reached 100% of loss in the generated power.

For minimize this loss, the 3M ® developed a strip made with high hardness material, in such a way to minimize the leading edge's erosion (http://solutions.3m.com/wps/portal/3M/en_US/Wind/Energy/Products/Wind_Protection_Tapes/). Furthermore, the maintenance of blades in this aspect becomes more agile, as, when it notices a level of erosion of this strip, it's enough that it be switched by a new one.

Studies about the effects of strips over airfoils are reported in the literature: (Cao & Wentz) have studied the placement of strips (called *transition strips*) throughout the entire wingspan of a model of eolic turbine, at approximately 5% of the chord in the upper camber and 10% of the chord in the lower camber and have concluded that, with the placement of one or two of these strips, there is an increment in the spike of power of the model from 0,21 to 0,23 kW. Similar results have been obtained too by Rasmussen (Rasmussen, 1984), which tested a rotor with NACA 63-212/24 and managed an increase in the spike of power in low Reynolds numbers.

So, it is intended, in this work, to study the effects of a strip fixed on the leading edge of an airfoil in two ways: study the effects that the strip itself causes in the flow over an airfoil and still study the influence of this strip added to the effects of rugosity caused over the time of utilization of the blade of a eolic generator

3 DEVELOPED ACTIVITIES

3.1 Simulations in Xflr5:

The first phase of the project was the realization of the computational analysis to obtain the two-dimensional aerodynamic behaviour of the used airfoils. The utilization of two-dimensional data of the airfoils in the forecast of the load upon the eolic generator's blade is valid in the sense of that is assumed that the speed's component around the blade is much greater than the radial speed's component, so that the flow in the blade's section is practically two-dimensional. This supposition is adequate until the point where occurs the separation of the boundary layer on the airfoil, which provokes that the fluid, with low quantity of movement in the region of separation, be subject to centrifugal and Coriolis forces, occasioning intense three-dimensional effects (Hansen & Madsen, 2011).

The utilized software was the XFLR5 program, which, for the 2D analysis, brings an interface for the XFoil program, which calculates the flow around the airfoil through the method of panels in addition to models of boundary layer. It is relatively precise in the phase previous to the separation of the boundary layer and stall, however, the

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equations that command the architecture of the program are not valid in the separation, so the estimative of maximum cl and the aerodynamic behaviour in the post-stall become imprecise (Hansen & Madsen, 2011). Not with standing, simulations were made in such a way to obtain initial forecasts about the airfoils.

The first step to the concretization of the simulations is to establish the condition in which the airfoils will operate, which implicates in the determination of the Reynolds number. The eolic generators operate in Reynolds numbers considered low when compared to planes or helicopters, typically under one million, even in the blade's tip (Leishman, 2007). Another fact to be considered is the capacity of the wind tunnel where the experiments will be done, in such a way that the Reynolds number of the simulations and the tests be the same and the comparison between the results be adequate. The wind tunnel where the experiments will be done has a section of tests of 460 mm by 460 mm and 1200 mm of length and the maximum speed reached by the tunnel is 30 m/s. It has been defined that the models would have 450 mm of wingspan, in such a way to avoid contact with the tunnel's walls, and 250 mm of chord. The speed of the flow in the experiments was defined as 20 m/s, as near 30 m/s the wind tunnel shown vibrations which could affect the quality of the results. The air's kinematic viscosity was considered as 1,6e-05 m²/s, which involves in a Reynolds number of 312500. The critic exponent of amplification (n_{crit}) used in the simulations in the XFoil, which represents the level of turbulence of the acting flow on the airfoil, was the pattern of nine.

So, the airfoils were simulated in the XFLR5 and the aerodynamic behavior was obtained. The characteristics that comprise the analysis are the curves of lift coefficient, drag coefficient, pitching moment coefficient and aerodynamic efficiency, all of them in terms of the angle of attack.

3.2 Model's construction:

The airfoils' models used were built in the work of (Daud Filho, 2012), the methods of construction and materials are present in the referred work (Daud Filho, 2012). To simulate the use of the protective strips on the leading edge, it has been opted for the utilization of 3M's 471 Strip (http://solutions.3m.com.br/wps/portal/3M/pt_BR/Construcao/Home/Solucoes3M/ConstrRapidas/CanteiroObras/#6 e http://solutions.3m.com.br/wps/portal/3M/pt_BR/IndustriaAutomobilistica/Home/InformacoesAdicionais/SaibaMais/?PC_7_RJH9U5230GE3E02LECFTDQS0R7000000_), because it has a good thickness for the calculation of the influence of the protective strips. To calculate this thickness, it was used the data of the article of (Guigère & Selig, 1999), doing a rule of three comparing the strip's thickness with the respective chord of the model used in the experiment.

The strip were stuck in two configurations: one covering from the leading edge to 7.5% of the chord (Fita 7.5%), at present used in blades of real generators, and the other one going to 27% (Fita 27%) of the chord, to verify if it would have an increase in the aerodynamic performance with and without rugosity.

To choose the granulometries of sand, it was used the following equation:

$$k/c > 900/\mathrm{Re} \tag{1}$$

Where k represents the size of the impurity, c the chord and Re the Reynolds number, in this equation if the fraction at the left obeys to the relation, the transition of the boundary layer will occur (Nascimento, 1998). So, it was possible to find the values of the sizes of the sand grains for this transition situation, which was a grain size of 0,625 mm. To verify the possibility of collecting this grain, the rule (NBR) was consulted, which brings a list with openings of available sieves. After consulting this rule, it was verified the availability of the needed sieves in the Department of Geotechnics of USP – São Carlos, and then their sieving was made. The sieving method occurred by letting through a grain of desired size and then restricting it, so it was obtained grains within an interval of sizes from 0,589mm to 0,710mm.

The method of fixation of sand in the experiment occurred by sticking a double-sided strip in the desired region, from the leading edge to 7% of the chord, region that is mainly affected by the rugosity. Sand was wiped over this surface in such a way to only stay fixed at the airfoil a single sand layer in such a way to create the size of the expected rugosity. The double strip did not offered the desired fixation, in spite of being very useful in the creation of only one sand layer, so a thin layer of spray varnish was wiped over to guarantee the fixation of the sand during the experiment.

3.3 Test in wind tunnel

Figure 1 – Schematic of the experiments

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With the airfoils' models ready, the experiments in wind tunnel have been initiated. Methods of measurements and corrections are the same present in the work (Daud Filho, 2012), which were based on (76028, 1995).

4 RESULTS

At first, the data obtained from the XFLR5 program was compared to the data obtained from the tests where were used the clean models (without the strips or rugosity)

After that, tests with the desired configurations for each airfoil were made.

4.1 DU93-W-210 Airfoil:

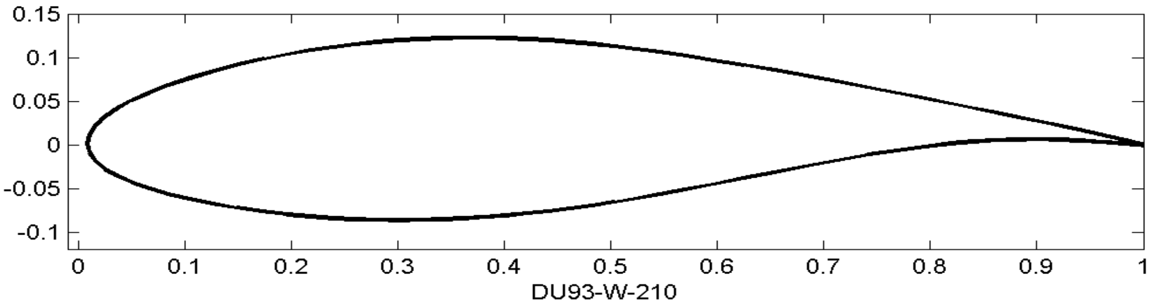

Figure 2: DU93-W-210 Airfoil

This airfoil has maximum camber position at 71.16%, maximum camber of 2.78%, maximum thickness position at 34.20% and maximum thickness of 20.68%, all related with the chord of the airfoil.

Cl is lift coefficient, *Cd* is drag coefficient, *Cm* is pitching moment coefficient *Cl/Cd* is efficiency aerodynamic, *Cp* is pressure coefficient and *c* is the chord.

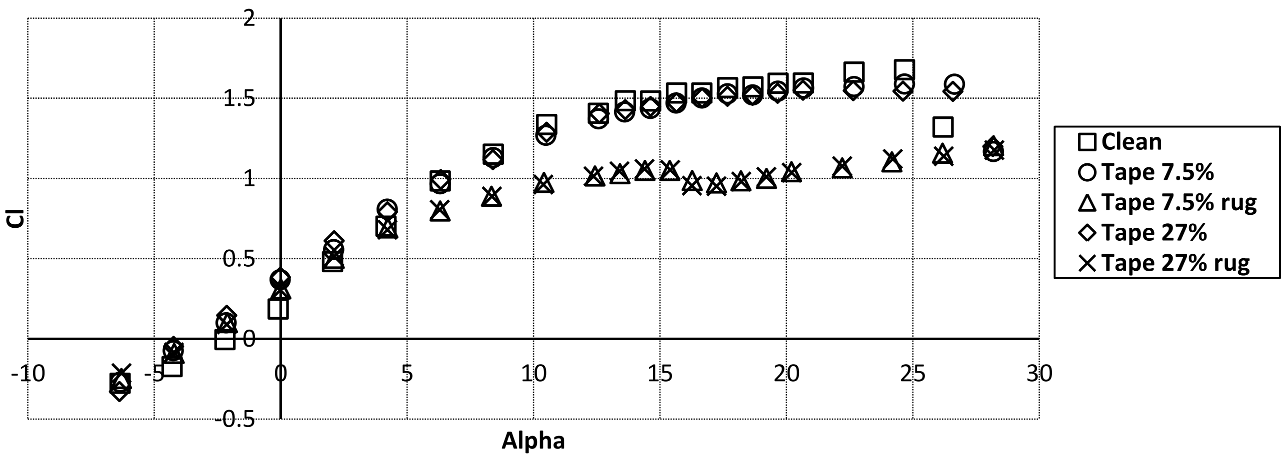

Figure 3: Comparison of the curves of Cl of the several configurations of colocation of tape and tape plus rugosity, for the DU93-W-210 airfoil

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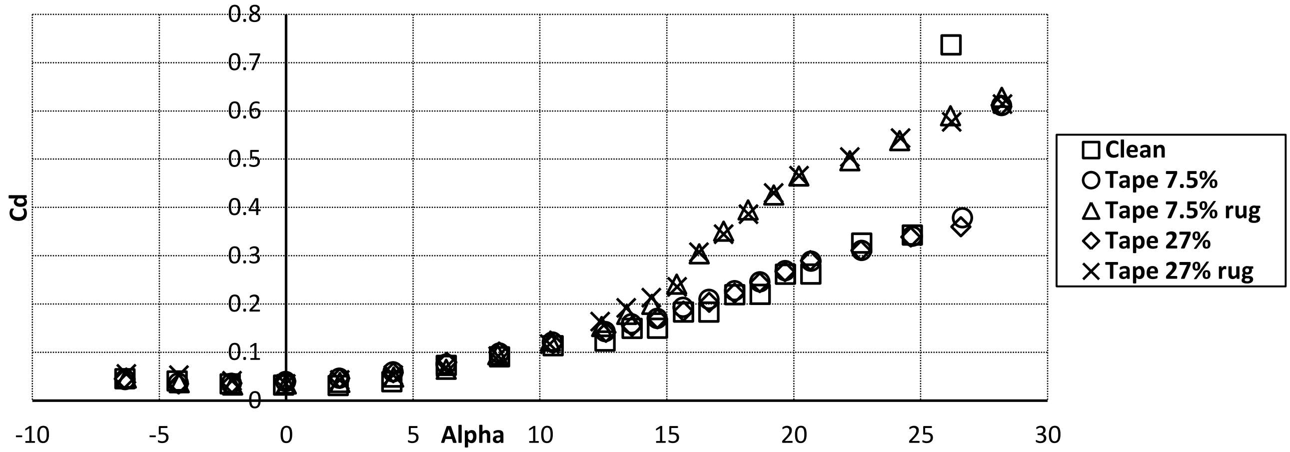

Figure 4: Comparison of the curves of Cd of the several configurations of colocation of tape and tape plus rugosity, for the DU93-W-210 airfoil.

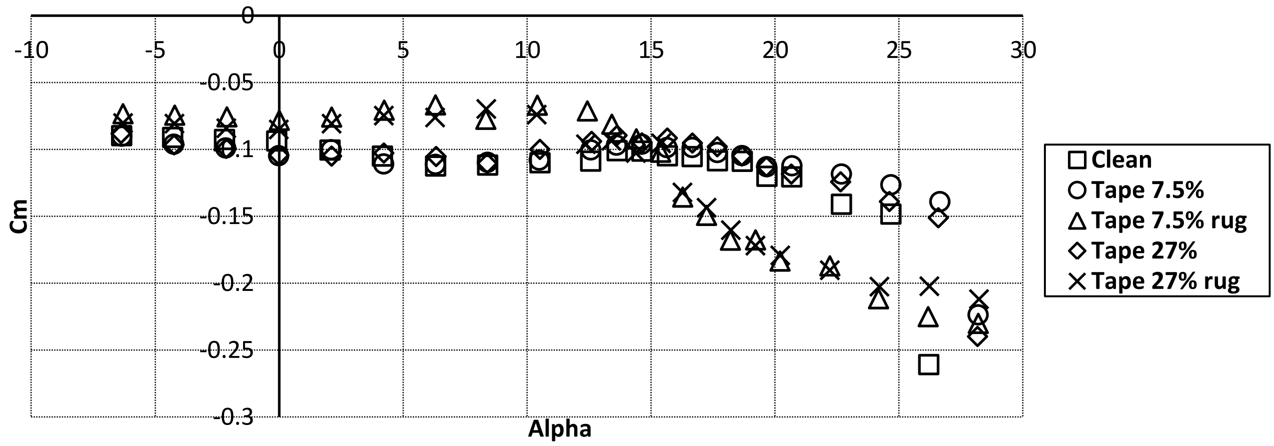

Figure 5: Comparison of the curves of Cm of the several configurations of colocation of tape and tape plus rugosity, for the DU93-W-210 airfoil.

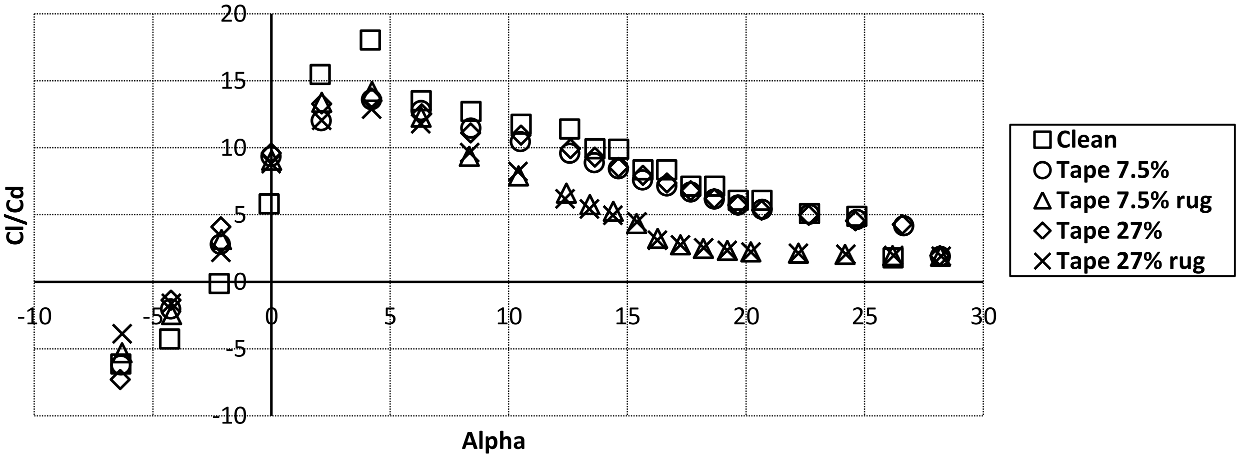

Figure 6: Comparison of the curves of Cl/Cd of the several configurations of colocation of tape and tape plus rugosity, for the DU93-W-210 airfoil.

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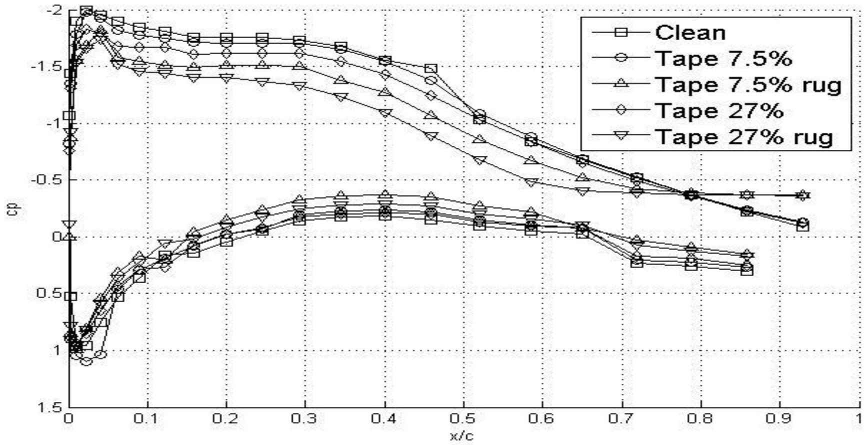

Figure 7: Curve of Cp along the chord for DU93-W-210 and alpha = 8º.

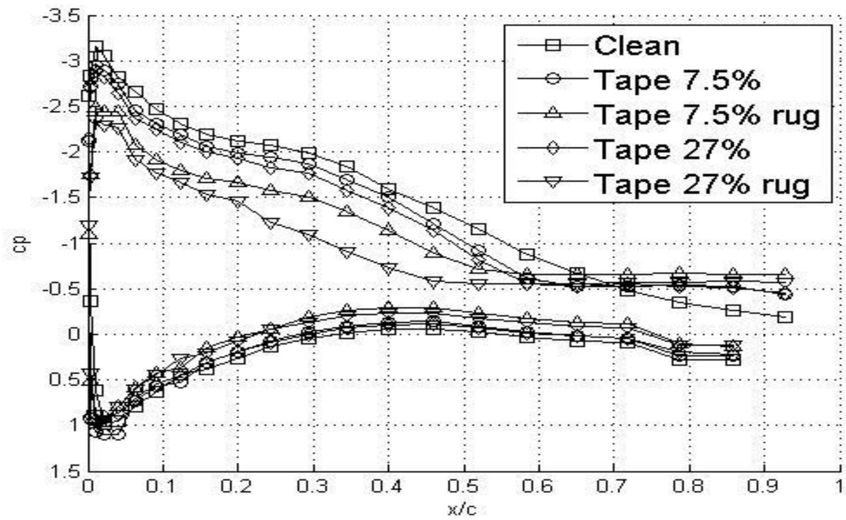

Figure 8: Curve of Cp along the chord for DU93-W-210 and alpha = 12º.

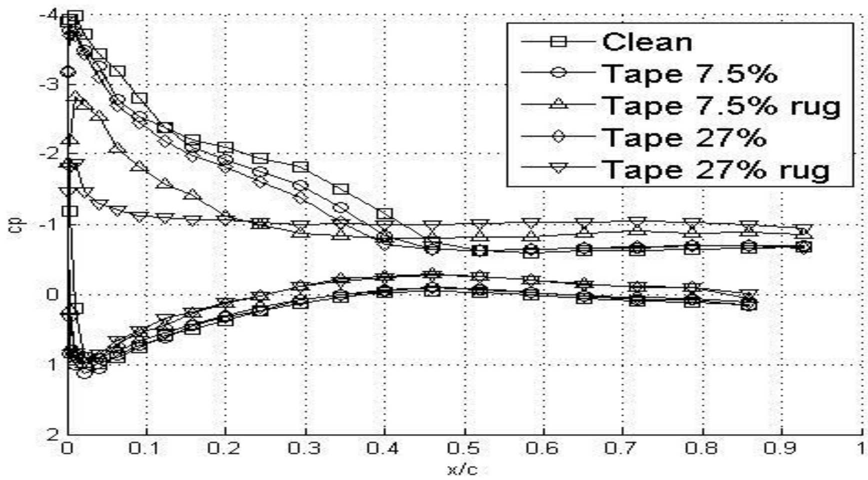

Figure 9: Curve of Cp along the chord for DU93-W-210 and alpha = 16º.

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The inclination of the curve of lift coefficient was more elevated in the computational simulation and this showed a spike at 10º that did not occurred in the experiment, which had values practically constant from 11º on. The coefficients of drag, pitching moment and aerodynamic efficiency were very distinct.

As we can see at the curve of *Cl*x*Alpha*, the "*clean*" configuration has a *Cl* a little bit higher than the configurations "*7.5% tape*" and "*27% tape*", what is justified by analyzing the graphics of *Cp*, because the curve of the "*clean*" one is always above the other two. Analyzing the curve of *Cd*x*Alpha*, we see that the configurations with strip has a *Cd* a little bit higher than the configuration without strip for angles above 10º, for lower angles we have practically the same *Cd*, as we can see at the graphics of *Cp* where to the configurations with strip the transition occurs before the configuration without strip.

For the configurations with strip, we see a very similar performance where the curves of *Cl*x*Alpha* and *Cd*x*Alpha* are practically the same, only for the alpha near the stall that the *Cl* for the configuration with strip until 7.5% stays a little bit above the other configuration, what can also be seen in the graphics of *Cp* that for medium little angles the two curves superpose each other and then for big angles the curve of the 7.5% strip stays a little bit above the curve of 27%.

In the configurations with rugosity, we have an expected loss of performance of the airfoil. This occurs, as we see at the graphics of *Cp*, because these configurations induce turbulence in the boundary layer, which makes that the boundary layer gets through a transition and separates before the other configurations. This can be observed already for an alpha of 16º, where for the configurations with rugosity the boundary layer already is almost completely separated and for the other configurations we have a stretch where the boundary layer is still attached.

4.2 FFA-W3-211 Airfoil:

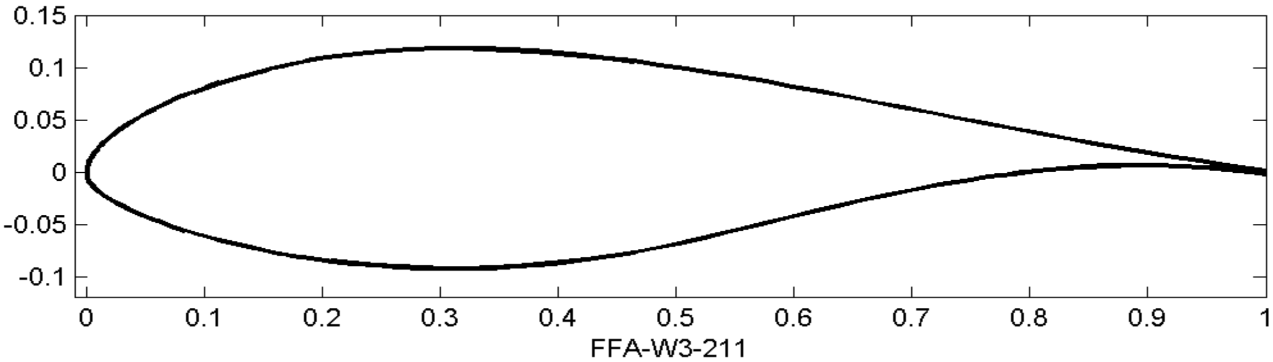

Figure 10 - FFA-W3-211 Airfoil

This airfoil has maximum camber position at 70.20%, maximum camber of 2.18%, maximum thickness position at 31.70% and maximum thickness of 21.09%, all related with the chord of the airfoil.

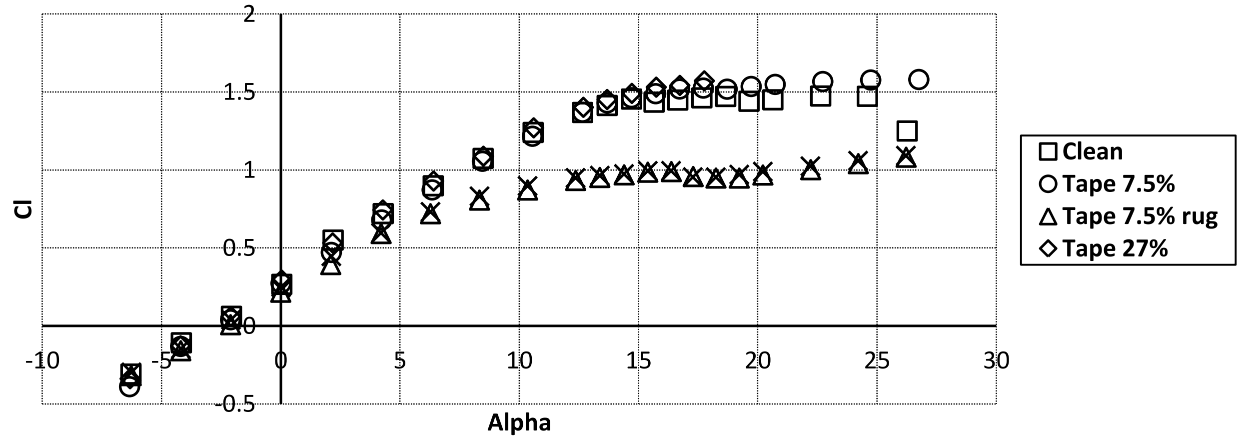

Figure 11: Comparison of the curves of Cl of the several configurations of colocation of tape and tape plus rugosity, for the FFA-W3-211 airfoil.

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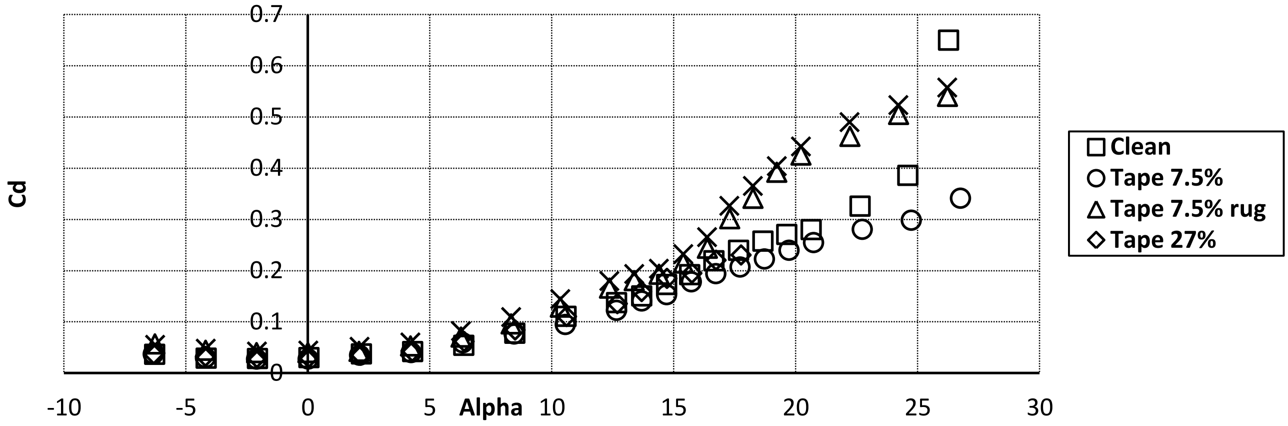

Figure 12: Comparison of the curves of Cd of the several configurations of colocation of tape and tape plus rugosity, for the FFA-W3-211 airfoil.

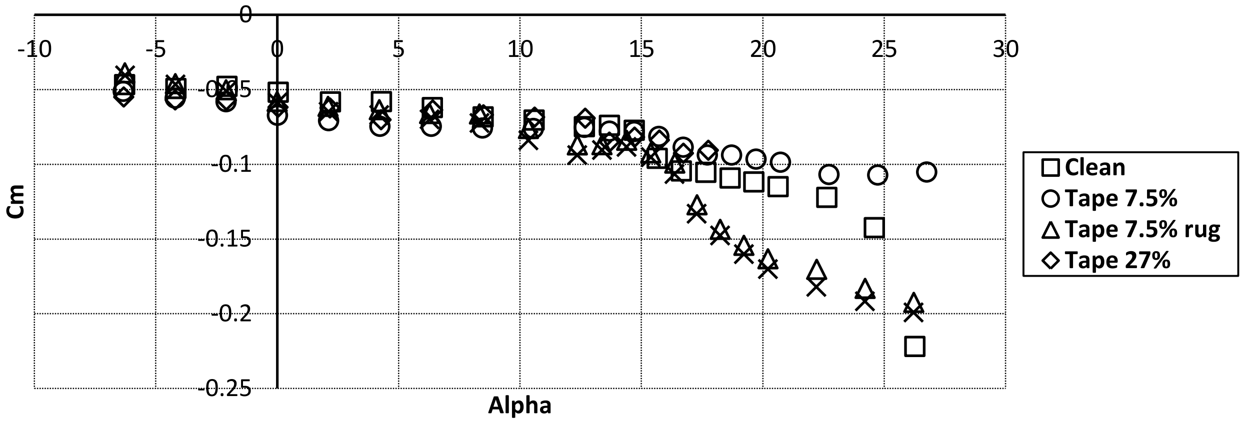

Figure 13: Comparison of the curves of Cm of the several configurations of colocation of tape and tape plus rugosity, for the FFA-W3-211 airfoil.

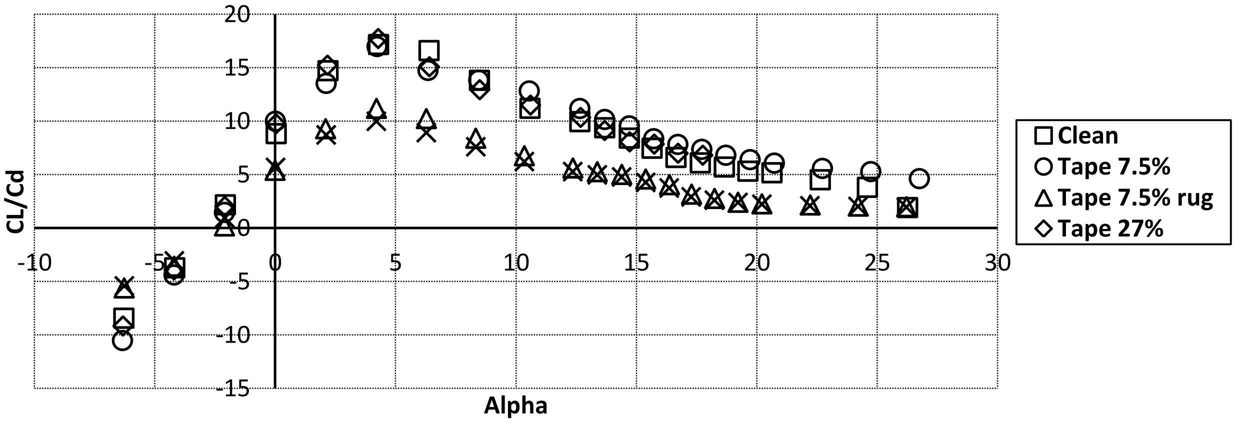

Figure 14: Comparison of the curves of Cl/Cd of the several configurations of colocation of tape and tape plus rugosity, for the FFA-W3-211 airfoil.

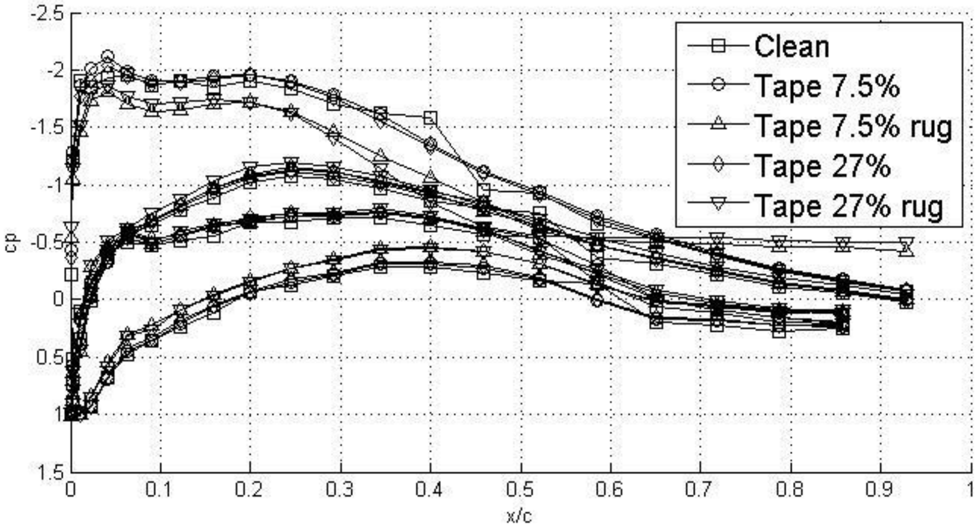

Figure 15: Curve of Cp along the chord for FFA-W3-211 and alpha = 8°.

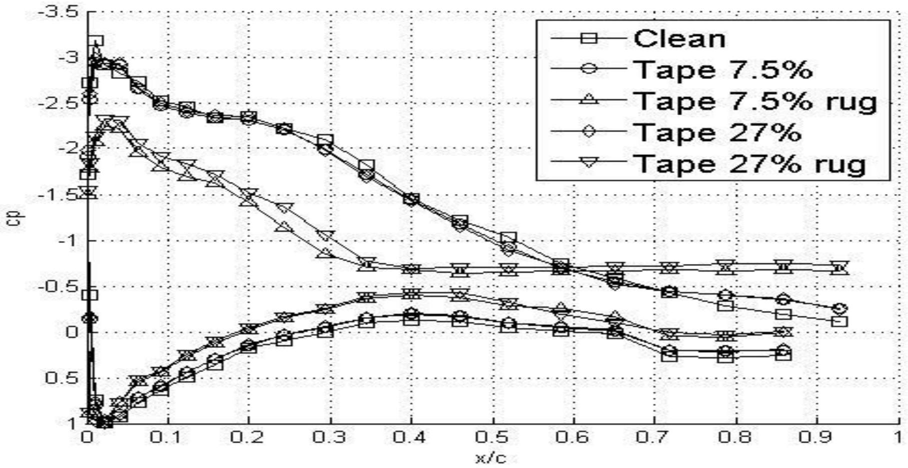

Figure 16: Curve of Cp along the chord for FFA-W3-211 and alpha = 12°.

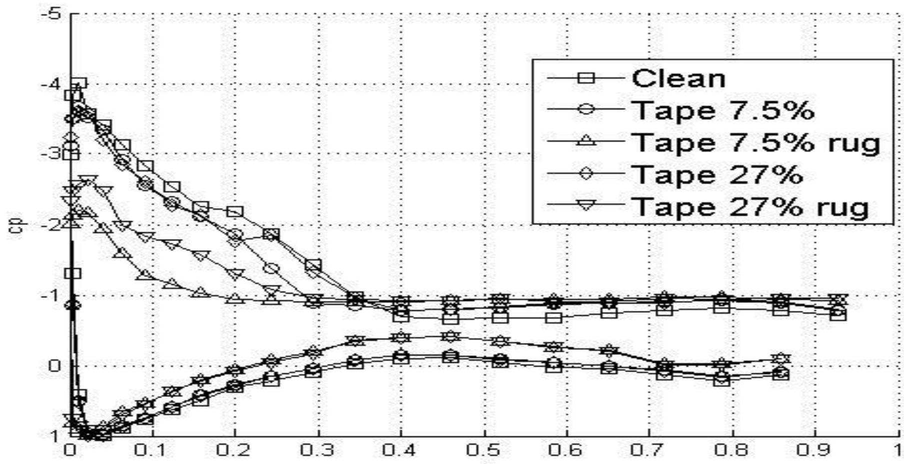

Figure 17: Curve of Cp along the chord for FFA-W3-211 and alpha = 16°.

Comparing the results of the computational simulation by the XFLR5 and the experiment with the model of the FFA-W3-211 "*clean*" airfoil, it was verified differences in the inclination of the curve of lift coefficient by angle of attack, and also for the value of maximum *Cl*, however the behaviour in post-stoll was practically the same. As expected, the values of drag coefficient by XFLR5 showed to be lower than the ones in the experiment, what was repeated for the majority of the other models, consequently the curves of aerodynamic efficiency (*cl/cd*) become very different. The curves of pitching moment were very similar from 14º on.

As we can see in the graphic of *Cl*x*Alpha*, the values of *Cl* for the configurations "clean", "*7.5% tape*" and "*27% tape*" remain practically the same, until that for angles above 15º, region near the stall, the value of *Cl* for the configuration "*clean*" falls in relation to the others, staying under them. This is showed in the graphics of *Cp* where, from 14º on, the curves of the configurations with strip have an area under the curve bigger than the configuration without strip.

Analysing the graphic of *Cd*x*Alpha*, we notice that for low and medium angles the value of *Cd* for the three configurations remains the same. Until that, from 10º on, the *Cd* of the configuration "*7.5% tape*" starts to have the curve of *Cd* under the curves of *Cd* of the other two configurations, which continue the same. It is believed that this occurred because the strip decreased the size of the resulting trail of the airfoil, decreasing its drag.

Comparing only the configurations with strip without rugosity, we notice that they have a similar aerodynamic performance, seeing the results we see that their curves are near enough to be within the measurement's error of the experiment.

For the configurations with rugosity, we see an expected loss of performance. This occurred for the same reason explained in the case of the DU 93 W210 Airfoil.

4.3 NACA 63415 Airfoil:

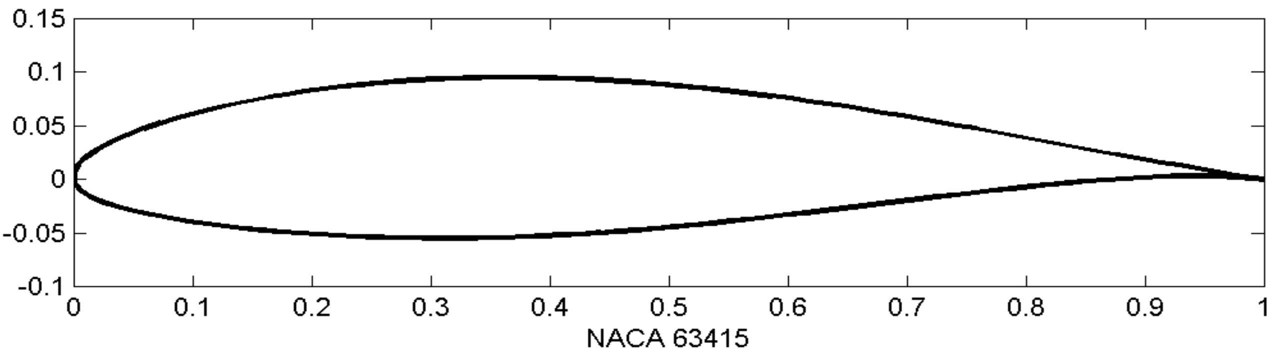

Figure 18: NACA 63415 Airfoil**.**

This airfoil has maximum camber position at 50.8%, maximum camber of 2.21%, maximum thickness position at 34.80% and maximum thickness of 15.00%, all related with the chord of the airfoil.

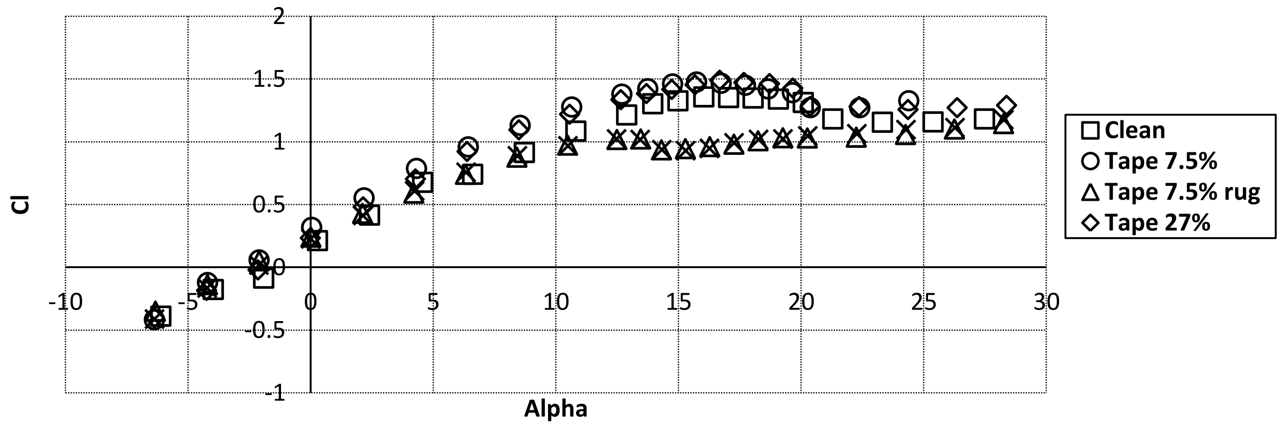

Figure 19: Comparison of the curves of Cl of the several configurations of colocation of tape and tape plus rugosity, for the NACA 63-415 airfoil.

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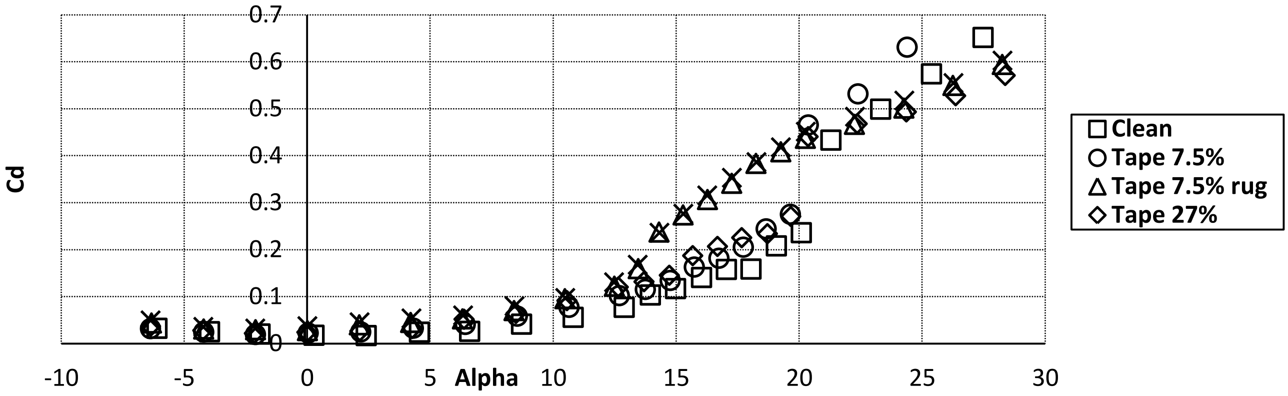

Figure 20: Comparison of the curves of Cd of the several configurations of colocation of tape and tape plus rugosity, for the NACA 63-415 airfoil.

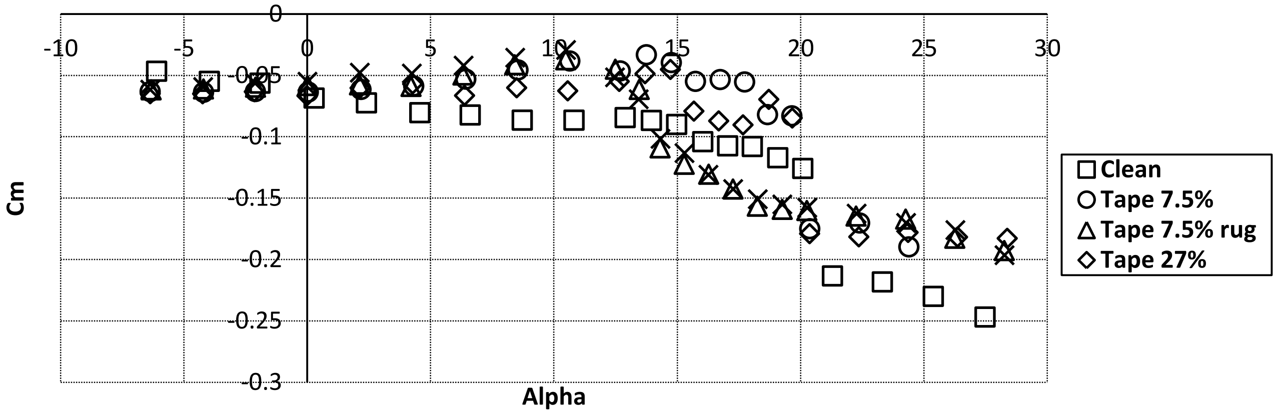

Figure 21: Comparison of the curves of Cm of the several configurations of colocation of tape and tape plus rugosity, for the NACA 63-415 airfoil.

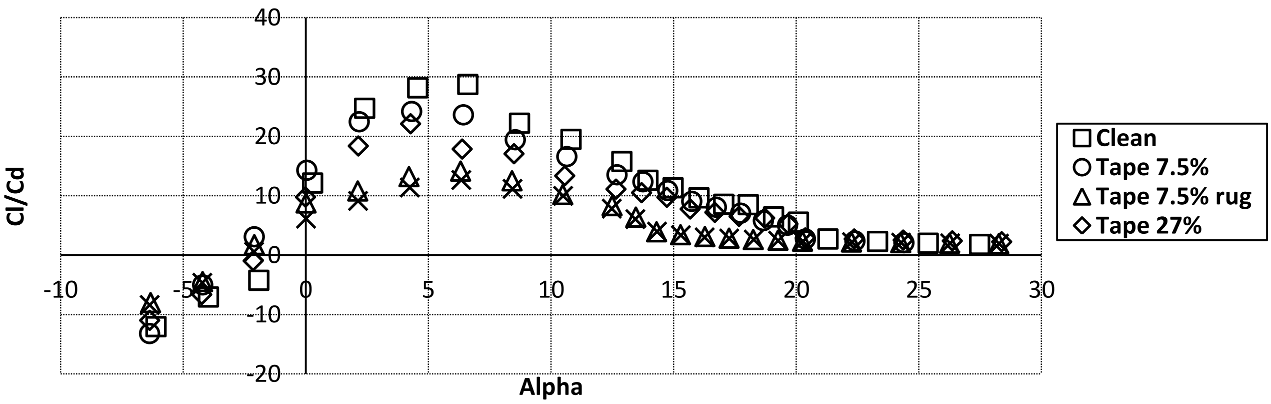

Figure 22: Comparison of the curves of Cl/Cd of the several configurations of colocation of tape and tape plus rugosity, for the NACA 63-415 airfoil.

Considering the comparison between the experiment and the computational simulation, it was verified that the inclination of the curve of lift coefficient by the XFLR5 is bigger and the maximum Cl by the experiment was higher. In low angles of attack the drag was similar, however with the increase of alpha there is divergence, and again the aerodynamic efficiency was very different, but the angle in which occurs the relation of maximum was the same.

Analyzing the graphic of ClxAlpha for the configurations “clean”, “tape 7.5%” and “tape 27%”, we notice that the configurations with tape obtained a curve of Cl above of the configuration “clean”. This is because the thickness of the tape induces that the boundary layer become turbulent, avoiding that this one separates. A fact that evidences this is the curve of CdxAlpha, where the configurations with tape had a drag bigger than the other configurations, showing that the boundary layer has become turbulent before, generating, then, more drag.

Comparing only the configurations with tape without rugosity, we notice that the curves stay within the interval of measurement's error of the balance, which shows that the two ones had practically the same aerodynamic performance.

Analyzing the configurations with rugosity, we see an expected loss of performance, for the same reason of the other airfoils.

When the acquisition of data of the NACA 63415 airfoil was made, it was noticed a failure in the measurements of the pressure taps for all the experiments of this airfoil, and as these experiments take too much time, including the preparation of the model, it was not possible to have enough time for the realization of these experiments again.

5 CONCLUSION

As we realize by the experiments, the airfoils with biggest maximum thickness DU 93 W210 and FFA-W3-211 did not suffered a positive aerodynamic influence, keeping practically the same curve of *Cl* that the configuration without tape, all for the case without rugosity, and for some cases even having a smaller *Cl*. This is due to their great thickness, which did not allow that the tape, a "generator" of vortices in the leading edge, induce the boundary layer to suffer its transition before and even increase the stall angle, preventing its separation. It could not induce the boundary layers, because as the thickness of the airfoils was very big, the boundary layer was already thick in such a way that the increase of the thickness of the tape to the airfoil was not enough to influence it, as we saw in the graphics of *Cp* for the two airfoils, where the transition for the three conditions "*clean*", "*tape 7.5%*" and "*tape 27%*" occurs practically in the same place.

For the NACA 63415 airfoil, as it has a maximum thickness quite lower and even small in relation to the others, it was possible to observe an increase in the *Cl* of the airfoil in conditions with tape. This is because exactly the same reason of the one explained above. This becomes more evident even by the fact of the increase in the *Cd*, which indicates that in these configurations the transition for the turbulent boundary layer occurred before. We had a decrease in the Cl/*Cd* of the configurations, because the increase in the *Cl* did not make up for the increase in the *Cd*.

Comparing the fact of using a tape or until 7.5% or in a value of until 27% of the chord, it was noted that there was not significant difference in the aerodynamic issues increase the interval of the tape along the chord in comparison with the configuration of tape until 7,5%. This was observed for the three tested airfoils. This is because the two configurations influence at the same way in the boundary layer. This is because the two configurations impose a vortex of equal size, because in the two configurations the "step" imposed over the airfoil has the same size.

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