Airfoil Selection Methodology for Small Wind Turbines

Valentín Salgado*‡, Cesar Troya**, Gustavo Moreno ***, Jaime Molina ****

*Department of Mechanical Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark

**Department of Mechatronics, Faculty of Applied Science and Technology, International University of Ecuador, EC170113 Quito, Ecuador

***Department of Engineering, Faculty of Mechanical Engineering, SEK International University, EC170302 Quito, Ecuador

****Department of Engineering, Faculty of Mechanical Engineering, SEK International University, EC170302 Quito, Ecuador

(valentinim676@gmail.com, cesartroyasherdek@gmail.com, gustavo.moreno@uisek.edu.ec, jaime.molina@uisek.edu.ec).

‡ Corresponding Author; First Author, Jose Maria Guerrero N70-222, EC170301, Tel: +593-983718751, valentinim676@gmail.com.

Abstract- On wind turbine technology, the aerodynamic performance is fundamental to increase efficiency. Nowadays there are several databases with airfoils designed and simulated for different applications; that is why it is necessary to select those suitable for a specific application. This work presents a new methodology for airfoil selection used in feasibility and optimization of small wind turbines with low cut-in speed. On the first stage, airfoils data is tested on XFOIL software to check its compatibility with the simulator; then, arithmetic mean criteria is recursively used to discard underperformed airfoils; the best airfoil data was exported to Matlab for a deeper analysis. In the second part, data points were interpolated using "splines" to calculate glide ratio and stability across multiple angles of attack, those who present a bigger steadiness were conserved. As a result, 3 airfoils, from an initial group of 189, were selected due to its performance above the average as exemplification of the methodology.

Keywords- Airfoil Selection Methodology; Low cut-in speed; Matlab Script; Small Wind Turbines; Spline Interpolation; XFOIL Simulation.

1. Introduction

Energy is the single most important challenge facing humanity today. [1]. In the last decades new energy solutions have been developed, but before opting for new energy technologies, it is necessary to re-enhance existing ones to meet energy demands in the short term. According to the World Nuclear Association Facts exposed by Larry Foulke [2] more than half of the world's population has no access to energy, so it is not just an energy production problem, it is also a problem of the distribution grid. In many places where there is no infrastructure for energy distribution, it is common to use methods based on fossil or biomass fuels to provide energy because they are portable and easy to use. However, those systems are in decline due to its high level of contamination and public health issues, so it is relevant to consider a renewable and easy to install energy source. Solar energy is a solution to compensate the energy requirement, but depending on the geographical location this methodology is not always feasible, either by low solar radiation received or unsuitable weather conditions in the area. Yet, wind energy is other mean to solve the energy deficit in far places using the small wind turbine (SWT) solution, a market that has experienced a growth in capacity installed in the last three years [3]. As stated at the IEC standards [4,5] a SWT produces between 1Kw to 15 Kw, it has a swept area less than 200m^2 and a minimum average wind speed of 6m/s, any other configuration is considered type "S" and the operating conditions are defined by the designer. The SWT catalogue [6] and the studies about SWT application for urban

environments [7] provided by the IEE, shown that 47% of SWT had cut-in speeds lower than 3m/s, but, the minimum rated wind speed is around 11m/s, that is the reason limiting SWT just for considerable wind speed applications. In order to increase sustainability of SWT for low wind speed applications, the first step is to increase efficiency by enhancing the aerodynamic performance of wind turbines. That is why the main objective of this project is to design a methodology of airfoil selection for wind turbines with a cut-in at 2m/s and producing energy at a speed rate around 4m/s until 6m/s in which production will keep stable.

2. Method

When designing a wind-power generator the average working speed is just the initial parameter in the analysis, it is also important to consider the atmospheric pressure, air density, air viscosity and the dimensions of the generator. Therefore a constant that relates these parameters is needed to characterize the air flow, the Reynolds number, henceforth called Re, will fulfill this condition. For this study the calculated values of Re meet the laminar flow parameters with 1.0×10^5, 1.3×10^5, 1.5×10^5, 1.8×10^5, 2.5×10^5 and 3.3×10^5. Also, an important identifier for the efficiency of an airfoil is the Glide Ratio (GR) which relates the lift coefficient (Cl) and the drag coefficient (Cd), the greater the GR the best is the Cl per unit of Cd.

For the present work, two institutions databases were used as a reference to obtain consistent airfoils with the objective stated: The Group of Applied Aerodynamics of the Department of Aerospace Engineering at the University of Illinois in Urbana Champaign (UIUC) [8], and the National Renewable Energy Laboratory USA (NREL) [9]. From UIUC 184 airfoils for low Re numbers were selected, initially studied to be used in unmanned gliders, wind turbines, aerobatic aircraft, sailplanes, etc. and 5 airfoils were selected from the NREL, 3 of them were designed for wind turbines with rotors of 1 to 3 meters of diameter and the other 2 were designed for wind turbines with rotors or 3 to 10 meters of diameter.

The analysis was performed on XFOIL software developed by Mark Drela with XFLR5 graphical user interface, the software was selected due to its analysis orientation on low Re airfoils by using an inviscid linear-vorticity panel method with a Karman-Tsien compressibility correction. As Drela [10] explains, there is a variety of methodologies for airfoil simulation; however, only the approach from the analysis of viscous / inviscid zones has proven to be fast and reliable on low Re flows. Therefore, working with Re less than 0.5 million become especially severe and only the ISES (A two Dimensional Viscous Aerodynamic and Analysis Code) [11] can predict low Re number airfoil flow fields. The reliability of this method of analysis is proven in previous tests by Drela [10] where errors between 0.085 and 0.766% were found on XFOIL simulations regarding laboratory measurements; other researchers as Fuglsang [12] have used the software as a validation method for wind tunnels and measuring systems.

To set up the simulation it was necessary to create a batch analysis considering 3 constant parameters, and a variable factor for each process. The first assigned parameter was Re, then, due to the wind speeds considered for this study, the calculated value of the Mach number did not exceed 0.2. The software considers values under 0.3 as incompressible flow, so any value below is discarded and the return value in the results is 0 [13], for this reason the Mach number was defined as 0 for every batch analysis. Finally, the "Ncrit" (n) of the free transition criterion e^n, is the factor that amplifies the frequency in which the fluid enters in transition, this value depends on environmental perturbations in which the airfoil will operate. For Ncrit a value of 9 was selected, which has been demonstrated that adequately reproduce the conditions of a normal wind tunnel; further tests by Chen [14] have concluded that efforts to improve the accuracy of this value gave insignificant variations in the outcomes. The angle of attack (α) was defined as the independent variable in the simulation with values between 0 and 10 degrees, in this range the maximum Cl is reached, surpassed these values of α would cause generator's stagnation. To ensure that all values were calculated by the program 1.0×10^4 iterations were established.

The proposed methodology needs four rounds of simulation and elimination. The first round is to prove the functionality of the airfoils in the program and discard the ones in which the software indicates a message of invalid compressibility correction factor. On the second round, the remaining airfoils were simulated and from the obtained data the mean value of the maximum GR (Max-GR) at Re equal to 1.0×10^5 and Re equal to 3.3×10^5 were calculated, airfoils with a Max-GR below of the mean value were discarded, then the difference between the maximum α at Re equal to 1.0×10^5 and Re equal to 3.3×10^5 were determined and those airfoils that return a value bigger than 2 degrees, 20 percent of determined range, were dismissed. The elimination criteria of the third round of simulation considered that the value of the Max-GR would not decrease more than 10% in a range on 0.5 degrees of its α. Finally, from the fourth round the data of the preserved airfoils were exported to a '*.csv' file to be tabulated and processed.

For data processing a script on Matlab software was created. The script accessed the file "*.csv" transforming it into a data table stored in a single array variable, then a local function separates the matrix into 4 one-dimensional arrays, each one containing a parameter of the information as follow: airfoil name, α, GR, and Re. Then, the arrays were stored in a file formatted with "*.mat" extension which is loaded automatically in subsequent processes, it is important to notice that each position in the table corresponds to the number of the sample being analyzed. A second script is responsible to extract the values of GR in each α separating them into sub-arrays "Y_i" according to the Re under which the sample was taken, the array containing the values of α is called "X_i".

To improve resolution of the α vs GR plot, the values in "X_i" and "Y_i" were interpolated by cubic splines, this method offers a more continuous and real solution due to its

particularity of working with small intervals and cubic polynomials instead of 'n' number of points and a polynomial of degree 'n-1', the output of this process are two arrays named "XX_i" and "YY_i" each one with 800 new points. Then, the Max-GR, the α limits for a 95% GR efficiency, and the difference between the limits is extracted from the array. To illustrate the process, Figure 1 shows the α vs. GR function for a S2091 airfoil at 3.3×10^5 Re, where the Max-GR is 95.389, the lower limit is $\alpha_1 = 3.7096$ and upper limit $\alpha_2 = 7.6129$ giving a $\Delta\alpha$ of 3.9033.

The airfoil has to be stable at many α's as possible to ensure stability and maximum efficiency, so it is important to look for the highest values of GR and $\Delta\alpha$ among the airfoils analyzed. Figure 2 tabulates the value $\Delta\alpha$ for the studied airfoils and Figure 3 tabulates the maximum value of GR.

3. Results

From the first round of simulation 19 airfoils were dismissed due to a variety of internal errors in the XFOIL calculations. The second batch of simulations were subjected to a series of eliminations criteria, using the mean Max-GR at 1.0×10^5 Re 76 airfoils discarded, using the mean Max-GR at 3.3×10^5 Re 23 airfoils eliminated, afterwards, 26 airfoils were eliminated using the difference between the Max-GR angles at 1.0×10^5 and 3.3×10^5. Finally, 28 airfoils were dismissed if the difference between the Max-GR at 1.0×10^5 and 3.3×10^5 were less than the mean value.

The third round of simulation was performed with the remaining 17 airfoils of which 11 were eliminated because its Max-GR decreased more than 10% in a range on 0.5 grades of its α. The 6 airfoils used for the final analysis in matlab were: S1210, S2091, SD7034, S4061, S4180 and S4320, all obtained from the database of the University of Illinois and designed by Michael Selig. Finally, after the data processing, the airfoils that were selected for its best aerodynamic performance parameters were: S1210 Fig. 4, Fig. 7, the S2091 Fig. 5, Fig. 8 and SD7034 Fig. 6, Fig. 9.
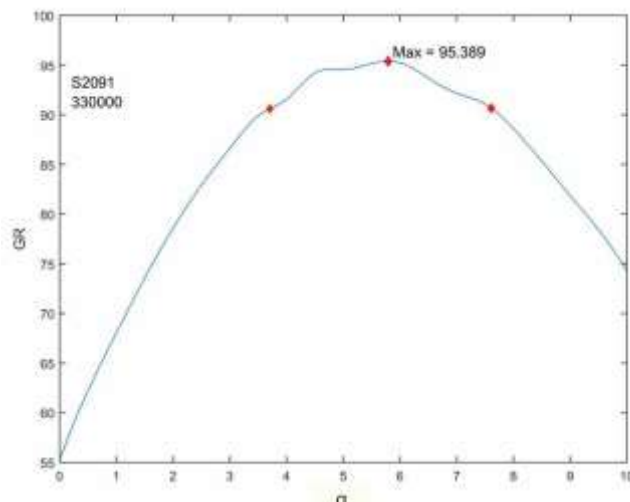

Fig. 1. Representation of 95% value of the Max-GR at 3.3×10^5 on S2091 airfoil.

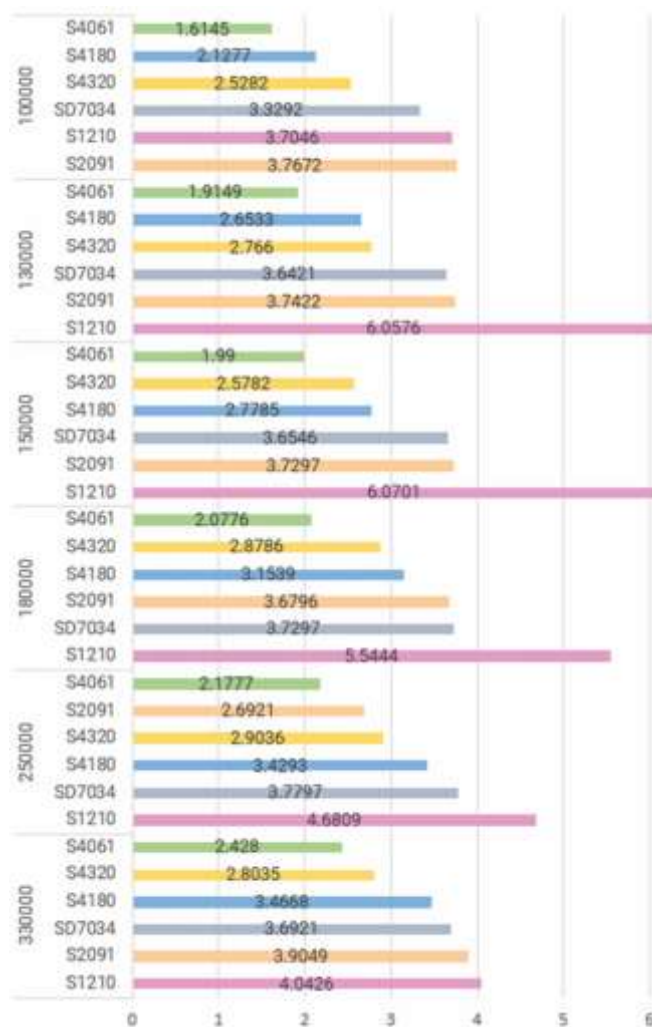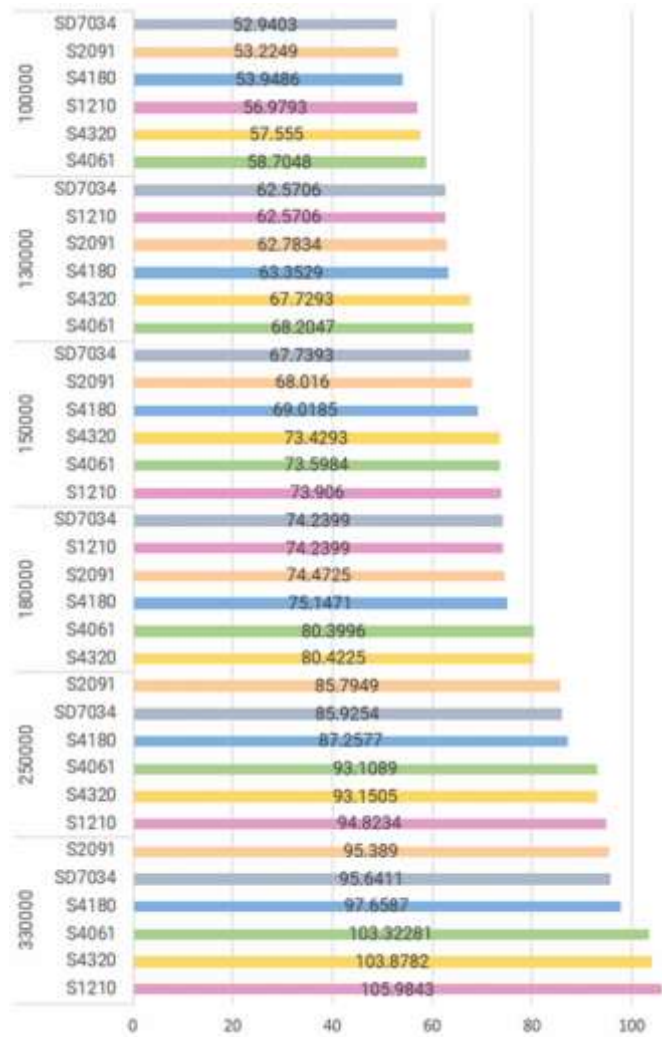**Fig 2.** Value of $\Delta\alpha$ for selected airfoils at different Re.

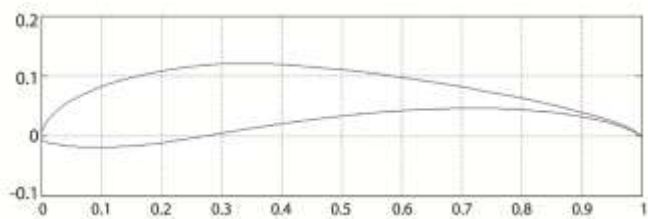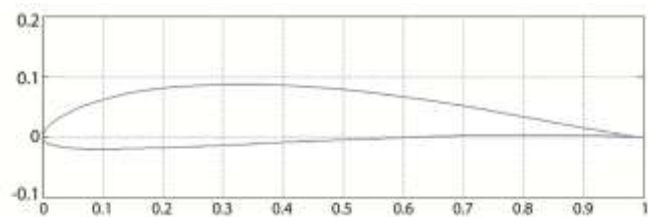**Fig. 3.** Value of Max-GR for selected airfoils at different Re.

Fig. 6. SD7034 Airfoil.

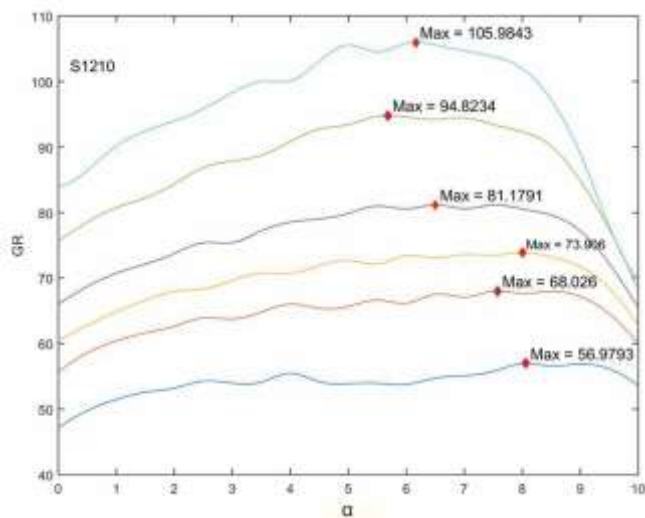**Fig. 7.** XFOIL Results of S1210 Airfoil.

Fig. 4. S1210 Airfoil.
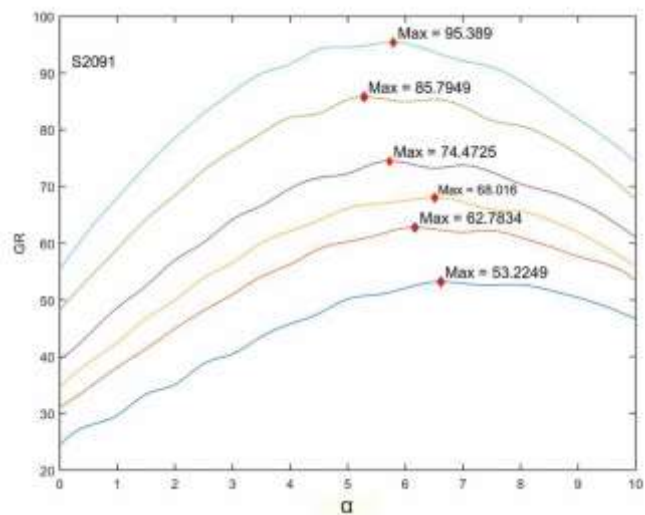

Fig. 5. S2091 Airfoil.

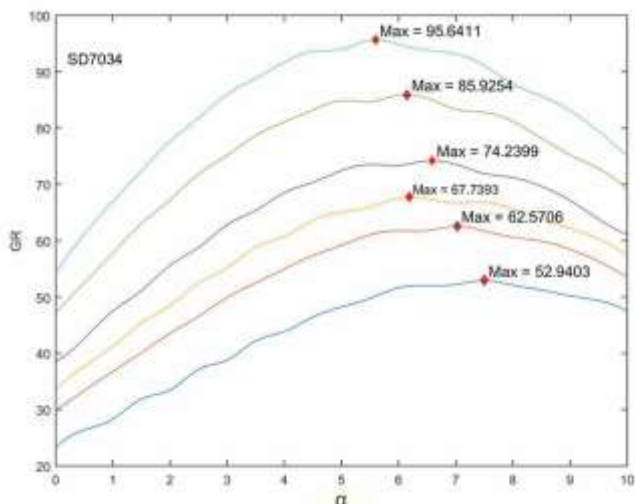**Fig. 8.** XFOIL Results of S2091 Airfoil.

Fig. 9. XFOIL Results of SD7034 Airfoil.

6. Discussion

The range of α from 0 to 10 degrees was defined considering that [15] demonstrates that only symmetric airfoils present lift over 10 to 16 degrees. Whereas, the curved airfoils used for wind turbines starts producing lift at 0 degrees but over 10 degrees they produced separation of the boundary layer and the airfoil enters in stagnation.

In the first round of simulation the discarded 19 airfoils presented inconsistencies in the step of calculating the aerodynamic coefficients, because the compressibility correction factors of Karman-Tsien used by the program were invalid. This is because the form of the airfoils is defined by the interpolation of its coordinates, in some cases the coordinates are not enough, so the airfoil geometry tends to be sharp at the leading edge. Similarly, this problem could cause that the upper and lower surfaces cross over on the trailing edge. The method used to make these airfoils suitable for the analysis is called "smoothing" that consists on the generation of more points from their established coordinates, and it could be made manually or with a special function of the software, but this is not the aim of the project.

After the second round of simulation and the data tabulation, the arithmetic mean was chosen as a disposal method. First, the airfoils with Max-GR to 1.0×10^5 below the average were removed because these would not guarantee optimal wind turbine cut in at the selected wind speed. Second, Airfoils with Max-GR to 3.3×10^5 lower than averages were discarded because these airfoils do not allow peak performance in power generation. Third, Airfoils whose difference between the α at Max-GR to 1.0×10^5 and the α at Max-GR to 3.3×10^5 was greater than 2 degrees were dismissed because this would generate instability in wind turbine operation. Normally wind turbines use a pitch control that is a system in charge to rotate the blade in order to optimize the operation and maintain the α as constant as possible, but this solution would increase the price of a SWT substantially. Lastly, the airfoils that had a range of Max-GR at 1.0×10^5 to Max-GR at 3.3×10^5 lower than the average

were removed, this allows detection of airfoils that had the desire cut-in performance, but they do not have a consistent peak efficiency and vice versa.

The third round of simulation consisted of 17 airfoils, at this point the determining factor was the stability values of Max-GR, of these airfoils 11 were discarded because although they had excellent values in all the above points, Max-GR were at specific points, with minimal variations of + -0.5 degrees the Max-GR substantially decayed less than 10%. Finally, of the 6 remaining airfoils 3 had lower efficiency as shown in Figure 2 and Figure 3, that is why the selected airfoils S1210, S2091 and SD7034 have Max-GR to 1.0×10^5 Fig. 10 and Max-GR to 3.3×10^5 Fig. 11 well above the average and superior stability at the α, having a range of 8 degrees at Max- GR do not decrease more than 5% Fig. 12, which makes them suitable for the application.
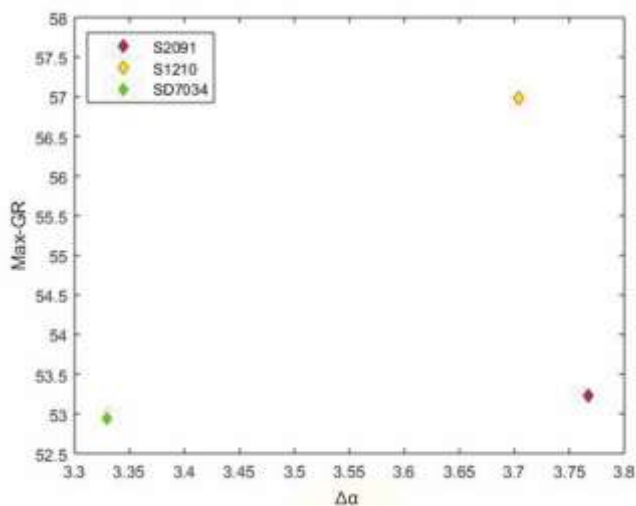

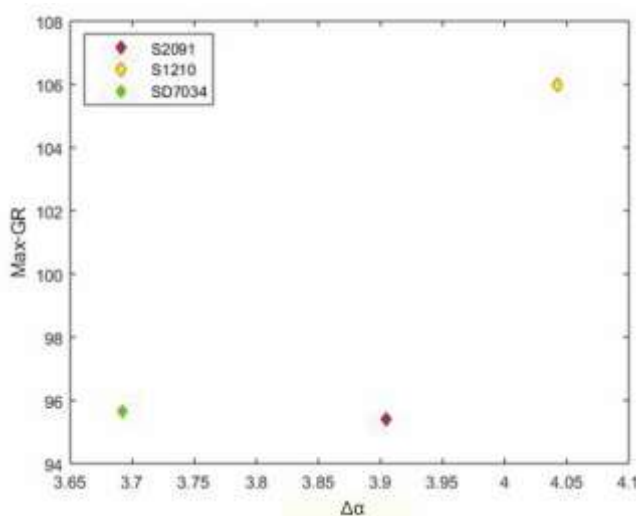
Fig. 10. Max-GR vs α at Re of 1.0×10^5.

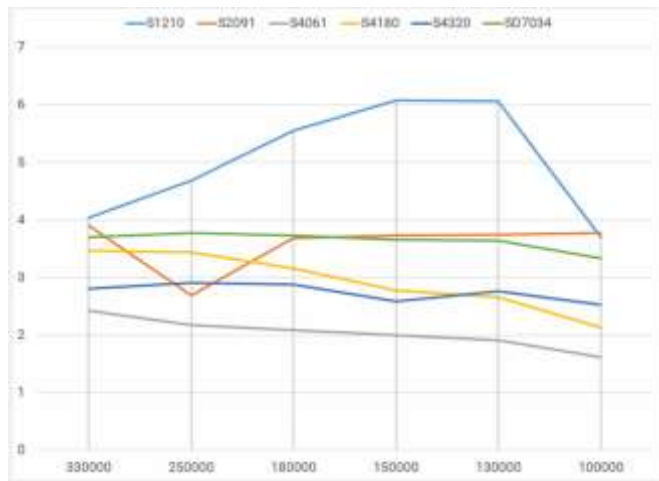**Fig. 11.** Max-GR vs α at Re of 3.3×10^5.

Fig. 12. Re vs. $\Delta\alpha$.

7. Conclusion

The main contribution is a methodology that allows a quick selection of airfoils; also, performance and stability parameters that facilitate the process of analysis were established as part of this work. The aforementioned parameters can be adjusted to other design requirements, according to users, maintaining the same selection methodology. Furthermore, a satisfactory analysis of 189 airfoils was achieved obtaining 3 suitable samples to use in low wind speed conditions.

As part of the methodology, XFOIL software was applied to reduce and facilitate the behavioral mathematical analysis of the selected airfoils at different Re. The spline interpolation method in Matlab allowed maintaining continuity in the airfoils performance plot to ease visualization and graphical analysis of airfoil performance at different angles of attack.

Although the selected airfoils are highly efficient aerodynamically, mechanical strength and manufacturing process are the following research projects in order to use them in the wind turbine production.

References

[1] Richard E. Smalley. *Our Energy Challenge.* Senate Committee on Energy and Neutral Resources. April 2004 (Conference).

[2] Foulke L. *A Look at Nuclear Science and Technology.* University of Pittsburg 2014.

[3] Pitteloud Jean-Daniel, Gsänger– *Small Wind World Report.* World Wind Energy Association. 2016 (Standards and Reports).

[4] Commission, I. E. *IEC 61400 - 2 Design Requirements for Small Wind turbines.* Geneva: International Electrotechnical Commission. 2008. (Standards and Reports).

[5] Commission, I. E. *IEC 61400-1 Wind Turbines - Design Requirements.* Geneva: International Electrotechnical Commission. 2008. (Standards and Reports).

[6] Intelligent Energy Europe – European Commission. *Catalogue of European Urban Wind Turbine Manufacturers* 2005 (Standards and Reports).

[7] WINEUR. *Urban Wind Turbines: Technology review.* Urbanwind. April 2007 (Technology review).

[8] UIUC Airfoil Data Site. M-selig.ae.illinois.edu. Retrieved 21 June 2016. URL: http://m-selig.ae.illinois.edu/ads/coord_database.html

[9] Wind Turbine Airfoils. Wind.nrel.gov. Retrieved 21 June 2016. URL: http://wind.nrel.gov/airfoils/

[10] Drela, Mark. *XFOIL: An analysis and design system for low Reynolds number airfoils.* Low Reynolds number aerodynamics. Springer Berlin Heidelberg, 1989, pp. 1-12. (Article).

[11] Drela, M., & Giles, M. B. *ISES: A Two-Dimensional Viscous Aerodynamic Design and Analysis Code.* AIAA Aerospace Sciences Meeting, Reno, NV, U.S.A. Marck 1987. (Article).

[12] Fuglsang, P., Antoniou, I., Sørensen, N. N., & Aagaard Madsen, H. *Validation of a wind tunnel testing facility for blade surface pressure measurements.* 1998. (Book).

[13] Mauclere X. Automatic 2D Airfoil Generation, Evaluation and Optimisation using MATLAB and XFOIL. DTU Mechanical Engineering. August 2009.

[14] Chen, Weisheng, and Luis P. Bernal. *Design and Performance of Low Reynolds Number Airfoils for Solar-Powered Flight.* AIAA Aerospace Sciences Meeting and Exhibit. 2008. (Conference Paper).

[15] Burton, T., Jenkins, N., Sharpe, D., & Bossanyi, E. *Wind Energy Handbook* 2nd ed. Chichester: Wiley. 2011. (Book).