INTRODUCTION

Blades are one of the most important parts in a wind turbine machine. In order to achieve maximum efficiency some shapes, dimensions and aerodynamic profiles are required for blades so manufacturing process of these parts requires quality inspection techniques. Several authors describe different techniques that have been implemented for aerodynamic profiles measurements of wind turbine blades. Notably, the speed testing is very slow due to the point-by-point measurement. In addition, the measuring range is restricted by the work table as objects larger than the dimensions of the table cannot be measured. Moreover, the cost of using CMM is relatively high. Laser radar technique (LR) is used to avoid errors of measuring data in marine wind turbine blades production generated by the deflection of wind turbine during inspection process and provide reliability in accuracy of data to blade manufacturers. Another quality...
inspection technique commonly used to evaluate a manufacturing process is photogrammetry,\textsuperscript{1} which allow evaluation of large-scale objects and have the advantage of being portable techniques. However, principal disadvantage of photogrammetry is the low sensitivity in measurements and that the process is very slow. In reference,\textsuperscript{2} authors compare LR with different measurement techniques under certain criteria and they conclude that LR presents important advantages over other techniques such as noncontact, high precision, large-scale object application, and portability but it is an expensive technique.

Laser triangulation techniques (LTT) are the most commonly used for 3D objects reconstruction, because these techniques are based on triangulation between the object, CCD, and projection of structured light. Height changes in a profile are measured from lateral displacements of points in a light line (structured light) projected on the object under test. Furthermore, LTT have simple structure characteristic, and measuring speed is fast and flexible, so there is a wide range of applications in the inspection and quality control of production process.\textsuperscript{12-18} However, principal disadvantage of LTT is the requirement of nonoutdoor illumination sources and color of surface under test, in such way that an additional image processing method is required in order to obtain digital reconstruction of the geometry of the wind turbine blade. In other work,\textsuperscript{19} the development of a low-cost scanner system is presented, and this system reconstructs a wind turbine blade using two projection and observation systems to evaluate both faces (extrados and intrados) of wind turbine blade. Different profiles of blade are reconstructed displacing it linearly by the use of a DC motor with feedback for position and speed control.

In this work, we present a proposal that uses only one projection and capture system, and to test both faces of blade, a mechanical system is used to rotate it an angle of 180 degree. In this way, this is a low-cost system but with the disadvantage of processing time operations and data interpretations.

2 | THEORY

Experimental arrangement used to reconstruct wind turbine blade geometry is based on the projection of a laser light line on a reference plane that is tangent to the surface under test in the point where sagitta is a maximum (ie, in the point on the surface with maximum thickness). To reconstruct one blade profile, laser light line is projected on a perpendicular way to the reference plane and a CCD camera captures the projected line on the surface (camera is placed in such way that it makes an angle $\phi$ with the reference plane), as we show in Figure 1. A direct computation shows that height changes in every single profile are given by

$$\Delta z = \frac{b \Delta x}{\Delta x + a \cot \phi},$$

where $a$, $b$, and $\phi$ are the CCD lens focal distance, pinhole-reference plane distance, and observation angle, respectively. $\Delta x$ is measured in the image plane, in pixels, and denotes lateral displacements of the reference light line produced by height changes, $\Delta x$, over selected profile along projected line.

To obtain an aerodynamic profile, blade is mounted on a mechanical system that transmits a $180^\circ$ degree rotation on the blade axis, which allows to measure both sides of the wind turbine blade, intrados and extrados. For a full blade scanning, we move optical system along blade axis, or $X$-axis, and reconstruct a set of profiles. This optical system is placed on a linear stage that is perpendicular to the $Z$-axis that allows small displacements associated with lateral displacements of projected laser line observed in the image plane of the camera (measured in pixels). Experimentally, parameters $a$, $b$ and $\phi$ are difficult to measure with good precision, so that by replacing them in Equation 1, data with significant errors are obtained. Instead of measuring these parameters we use a calibration method by calculating the $Z$ coordinate for each point $(X, Y)$ along the projected laser line on the surface of the wind turbine blade.

Sensitivity of our technique is obtained from Equation (1) taking into account that minimum displacement that can be measured by the CMOS sensor is of the order of 1 pixel. However, the resolution of the camera, the focal length, and the angle of observation are all involved in the measurement of sensitivity and should be taken into account.
Optical system measuring for digital reconstruction is formed by a laser diode module (0.9 mW, 633nm), a CCD camera (752 x 480 px) and the object under test (wind turbine blade). For the rotation of the profile, a stepper motor NEMA 34 of Applied Motion Products is used and is controlled by means of an Arduino Mega 2560 microcontrol card. To validate the method, the symmetric profile of the NACA family 0012 was used, which has the equation

\[
z = 5r \left[ 0.2969 \frac{\sqrt{y}}{c} - 0.1260 \left( \frac{y}{c} \right) - 0.1565 \left( \frac{y}{c} \right)^2 + 0.2843 \left( \frac{y}{c} \right)^3 - 0.1015 \left( \frac{y}{c} \right)^4 \right],
\]

where \( c \) is the length of the chord, \( t \) is the maximum thickness as a fraction of the chord, (see Figure 2), for the profile.

Experimentally, two profiles were reconstructed: the profile manufactured in polylactic acid (PLA) with the help of a 3D printer (Prusa I3 XL) and the metallic AF104 aerofoil profile, both are compared with the theoretical profile given by Equation (2). Figure 3A shows the profile AF100 with a chord length \( c = 150 \text{ mm} \) and a maximum thickness \( t = 18 \text{ mm} \). Figure 3B shows the profile manufactured in PLA, with the same dimensions. Experimental setup for the measurement of the profiles is shown in Figure 4. A calibration is previously
made with the help of a linear displacement stage that transmits a displacement of the projection and observation system on the Z-axis, and another stage with similar characteristics is used to move the system linearly on the X-axis and to measure the profile in another section of the blade.

The procedure for the measurement consists in adjusting the observation system to the field of view of the camera in such a way that the displacements are measured by the larger side of the sensor, to obtain the best resolution. An image is captured and a 180° rotation is applied to complete the profile in that section. Finally, we use an image processing method that allows to obtain discrete data describing profile under test. Afterward, the experimentally obtained profile is compared with the theoretical profile of the NACA 0012 family.

Calibration process in this proposal was made with linear displacements along Z-axis, in such a way that we can measure lateral displacement of a point on the image plane, which allow us to obtain calibration curve shown in Figure 5, with a sensitivity of 0.1 mm taking into account that minimal displacement that can be measured in the image plane is of the order of one pixel.

For the reconstruction of each test profile, measurements were taken along 4 sections, in particular only one of them was taken to compare the theoretical profile of Equation (2) with the testing profiles (real profiles). Figure 6 shows the results of the comparison of the measured profiles (AF104 and PLA) with the theoretical profile (NACA0012).

As we can see in Figure 6, set of points of the profile AF104 is closer to the curve of the profile NACA0012, obtaining absolute deviations (RMS) of the order of 0.0732 mm for the profile of PLA and 0.0373 mm in the profile AF104. The deviations of chord length are shown in Figures 7 and 8 for the profile of PLA and 0.0373 mm in the profile AF104. The absolute deviations (RMS) of the order of 0.07321 mm for the profile in another section of the blade. Finally, we use an image processing method that allows to obtain discrete data describing profile under test. Afterward, the experimentally obtained profile is compared with the theoretical profile of the NACA 0012 family.

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3.1 | Aerodynamic analysis

For the aerodynamic analysis of the geometries obtained from the measurement process in comparison with the reference profile NACA0012, Xfoil free software\(^\text{\ref{21}}\) was used, which is an interactive program for the design and analysis of isolated subsonic aerodynamic profiles. A range of Reynolds numbers \(Re\), used in the aerodynamic design of small wind turbines, of \(2 \times 10^5 \leq Re \leq 5 \times 10^5\) and range of angles of attack \(\alpha\) of \(-5^\circ \leq \alpha \leq 20^\circ\), is considered. Table 1 shows the values of maximum lift coefficient \(C_{l_{max}}\), drag coefficient \(C_{d}\), and angles of attack \(\alpha\) for the profiles NACA0012 (reference profile), AF104, and PLA.

As we can see for \(Re = 2 \times 10^5\), reference profile (NACA0012) has a maximum lift coefficient of 1.085 at \(\alpha = 12^\circ\), and for the PLA profile, the lift coefficient is 1.010 at an angle of attack \(\alpha = 10^\circ\). In this case, drag coefficient for the reference profile starts from 0.044 and increases as the lift coefficient decreases, for the PLA profile the drag coefficient increase also starts at 0.044 but at a lower angle of attack \(\alpha\).

For a number of Reynolds of \(Re = 5 \times 10^5\), the same behavior is maintained but now at higher lift values and angles of attack \(\alpha\). Drag coefficient values in this case increase, and this behavior of both lift and drag coefficients for the three profiles with \(Re = 2 \times 10^5\) can be better visualized in Figure 9. In Figure 10, we show the case when \(Re = 5 \times 10^5\).

Results obtained for drag and lift coefficients for the two Reynolds number evaluated in this work are attributed to factors that affect the transition of the boundary layer as the surface roughness\(^\text{\ref{22}}\) caused by the difference or error in manufactured wind turbine blade geometry.

Nowadays, ratio \(C_l/C_d\) is a widely used parameter to evaluate aerodynamic efficiency of a wind turbine blade profile. In this way, in Figure 11 we plot ratio \(C_l/C_d\) and angle of attack \(\alpha\) for the case of \(Re = 2 \times 10^5\) where values for this parameter are 47.46 and \(\alpha = 5^\circ\) for the case of NACA0012 profile, 44.40 and \(\alpha = 7^\circ\) for the case of AF104 profile, and 36.04 and \(\alpha = 6^\circ\) for the case of PLA manufactured profile. These maximum points of the curves in Figure 11 correspond to the angles of attack of maximum aerodynamic efficiency at which the torque forces necessary for turning the wind turbine are obtained. Furthermore, in Figure 12 we plot the efficiency of these wind turbine blade profiles for \(Re = 5 \times 10^5\), where reference profile has a value of 61.74 for an angle of attack \(\alpha = 6^\circ\), 62.20, \(\alpha = 8^\circ\) and 42.71, \(\alpha = 6^\circ\) for AF104 and PLA profiles, respectively.

These behaviors of \(C_l/C_d\) ratio for two cases of Reynolds numbers evaluated in this work depend among others on the geometry of the aerodynamic profile, observing that as the error generated in the scanning process of the geometry of...
the profiles AF104 and PLA increases, the lift coefficient decreases and the drag coefficient increases.

4 | SYSTEM SETUP FOR TESTING FX 63-137 PROFILE

The method was used for the quality test of the manufacture of a blade with profile FX 63-137 of 1.7 m in length, maximum thickness of 13.7% at 30.9% of the chord, and a maximum curvature of 6% at 53.3% of the chord. The blade was manufactured in the workshops of the Universidad del Istmo for a wind turbine of 1.5 kW nominal power, and the measurement technique was instrumented in the optical laboratory with other characteristics than the NACA0012 profiles test that facilitated the measurement process. The optical system was mounted on a motorized linear displacement plate on the Z-axis, which allows the system to be calibrated in a fast way and with good precision. In addition, the whole system is on a rail that allows to measure the profile of the blade in other sections, which were 3 mainly at 25%, 50%, and 75% of its length.

Figure 6 Comparison of data points measured in profiles AF104 and manufactured in PLA against the ideal profile NACA0012

Figure 7 Deviations of the PLA profile with respect to the reference profile NACA0012 for: (A) extrados and (B) intrados

Figure 8 Deviations of the AF104 profile with respect to the reference profile NACA0012 for (A) intrados and (B) extrados
shows the experimental setup for the reconstruction of the profiles.

Using the same methodology as in the NACA profile test, a similar value (0.1 mm) of sensitivity of the instrument was obtained on the Z axis for this case.

The blade under test has a theoretical design profile FX 63-137 family, where the tabulated profile information is provided in the database, unlike the NACA profile where there is a continuous function that describes the profile (Equation 2). Figure 14 shows the plot of the theoretical profile.

Using the same procedure for the reconstruction of profiles, we measured three profiles at three different positions respect to the total length of the blade under test, at 75% (P1), 50% (P2), and 25% (P3). The qualitative results can be seen in Figure when comparing the profile measured with the optical method and the reference profile FX 63-137. Differences can be observed in some regions along the chord, in the extrados and intrados, which can be measured quantitatively by determining the deviations between the theoretical profile and the profile measured with the optical method. To determine the deviations, polynomial interpolation is used for the data set (n) of the reference profile to a polynomial of degree n – 1.

As can be seen in Figure 15, the theoretical profile FX 63-137 is scaled to each length of the section of the blade under test, and for each section, the differences are analyzed and are plotted (Figures 16 and 17), and the maximum deviations Δz_max and RMS Δz_rms of the 3 sections of both the extrados and the intrados are shown in Table 2.

Figures 16 and 17 show the quality errors in the blade manufacturing, so we can complement the information with

| TABLE 1 | Lift and drag coefficients for testing profiles AF104, PLA and reference NACA0012 |
|---------|------------------------------------------|
| Re = 2 × 10^5 | NACA0012 | AF104 | PLA |
| α | 12 | 12 | 10 |
| C_{l_{max}} | 1.085 | 1.094 | 1.010 |
| C_d | 0.044 | 0.045 | 0.044 |
| Re = 5 × 10^5 | α | 13 | 15 | 11 |
| C_{l_{max}} | 1.1938 | 1.1928 | 1.1388 |
| C_d | 0.0312 | 0.0574 | 0.0332 |

FIGURE 9  Lift (C_l) and drag (C_d) coefficients vs angle of attack (α) for Re = 2 × 10^5

FIGURE 10  Lift (C_l) and drag (C_d) coefficients vs angle of attack (α) for Re = 5 × 10^5
**Figure 11** Ratio $C/L_d$ vs $\alpha$ for $Re = 2 \times 10^5$

**Figure 12** Ratio $C/L_d$ vs $\alpha$ for $Re = 5 \times 10^5$

**Figure 13** Experimental setup for wind turbine blade test
an aerodynamic analysis by determining the lift and drag coefficients for the profiles measured by the optical method, similar to the analysis performed in Section 3 with profile NACA0012.

4.1 | Aerodynamic analysis

Figure 18 shows the effects of the lift coefficient ($C_l$) vs the angle of attack ($\alpha$) in the three sections: $P_1$ to 75% of the length of the blade, $P_2$ to 50%, and $P_3$ to 25%, respectively.

The lift coefficient of theoretical profile FX 63-137 has a maximum value of 1.8141 at an angle of attack of $15^\circ$; for the measured profile of the position $P_1$, a value of 1.2206 is obtained at an angle of attack of $5^\circ$, for the position $P_2$, a value from 1.4846 to an angle of attack of $14^\circ$ and for the position $P_3$, a value of 1.1220 for an angle of attack of $5^\circ$, it can be seen that for an angle of attack of $7^\circ$, it decreases to 1.0561 and finally for an angle of $20^\circ$ $C_l$ has a maximum of 1.4162. Up to these maximum lift values, the lift coefficient was increased as the angle of attack increases, from that angle (also known as the critical angle), the profile enters a loss of lift which is related to the detachment of the boundary layer.

If we consider the percentage of decrease in the lift coefficient after the maximum lift angle, the theoretical profile has 94%, the profile in $P_1$ has 78%, the profile in $P_2$ has 86%, and the profile in $P_3$ has 79%. The three profiles are found in a decrease greater than 55%, that is, the fall or loss of lift is gradual.

Figure 19 shows the effect of drag ($C_d$) coefficient against angle of attack ($\alpha$) in positions 1, 2, and 3 respectively.

In the theoretical profile when the lift coefficient begins to decrease, it can be seen that the drag coefficient begins to increase, and this value being 0.0891. If we consider about $3^\circ$ after the maximum lift coefficient, we can observe an increase in the drag coefficient up to 0.1476. For the profile of position 1, the value of the drag coefficient in the maximum lift angle is 0.0198, assuming $3^\circ$ after the maximum lift it obtains an increase of 0.0421. In position 2, the value of the drag coefficient in the maximum lift angle is 0.0838, assuming $3^\circ$ after the maximum lift, an increase in 0.1462 is obtained. In position 3, the value of the drag coefficient in the maximum lift angle is 0.0108, assuming $3^\circ$ after the maximum lift it obtains an increase of 0.0274.

Figure 20 shows the effects of aerodynamic efficiency of the profile (ratio $C_l/C_d$) against angle of attack ($\alpha$) in positions 1, 2, and 3, respectively. In theoretical profile, the maximum aerodynamic efficiency of the profile is $4^\circ$ with a value of 120.16. For the profile in position 1, the maximum ratio is obtained at an angle of $2^\circ$ with a value of 108.068, and the decrease in the maximum value with respect to the original profile is 10.1%; in profile 2, the maximum ratio is obtained at an angle of $3^\circ$ with a value of 103.694, and the decrease
in the maximum value with respect to the original profile is 13.7%; and for profile 3, the maximum ratio is obtained at an angle of 4° with a value of 110.145, and the decrease in value maximum with respect to the original profile is 8.3%.

Table 3 shows the values of maximum lift coefficient $C_{l_{max}}$, drag coefficient $C_d$, and angles of attack $\alpha$ for the theoretical profile FX 63-137 (reference $^{24}$), and measured sections $P_1$, $P_2$, and $P_3$. 

**FIGURE 16** Deviations of the measure profile with respect to the reference profile FX 63-137 (Extrados), (A) to 75% of the length of the blade, (B) to 50% and (C) 25%

**FIGURE 17** Deviations of the measure profile with respect to the reference profile FX 63-137 (Intrados), (A) profile at 75% ($P_1$) of the length of the blade, (B) to 50% ($P_2$) and (C) 25% ($P_3$)
DISCUSSION AND CONCLUSIONS

Our technical proposal of an optical profilometer in order to measure wind turbines blades profiles has the advantage that it can be adapted to linear translation systems for the measurement of large wind turbine blades, and that it uses a capture and light projection system which makes it a low-cost instrument compared to commercial scanner systems. The

| Section profile | Extrados | Intrados |
|-----------------|----------|----------|
|                 | $\Delta z_{\text{rms}}$ | $\Delta z_{\text{max}}$ | $\Delta z_{\text{rms}}$ | $\Delta z_{\text{max}}$ |
| 25%             | 0.33     | 1.19     | 0.46     | 1.38     |
| 50%             | 0.31     | 1.08     | 0.87     | 1.45     |
| 75%             | 0.28     | 1.32     | 1.05     | 2.72     |

FIGURE 18  Lift ($C_l$) coefficients vs angle of attack ($\alpha$) for $Re = 5 \times 10^5$. A, Profile in $P_1$, B, profile in $P_2$ and C, $P_3$.
The purpose of this instrument is to reconstruct and measure wind turbine blade profiles manufactured in our laboratory and evaluate the quality of its manufacture by comparing them with the ideal profiles, or design profiles, as well as to test the real profiles in the Xfoil software for profiles analysis.

As is well known, distortion is an aberration commonly seen in several procedures of image acquisition and is manifested by changes in the shape of an image rather than the sharpness or color spectrum. Nevertheless, in our case images obtained by CMOS camera are not affected by this kind of distortion since the image of the projection of the laser line on the blade is captured in the central part of the CMOS camera, in a region of the order of 2.6% with respect to the largest side of the CMOS sensor, what makes defects in the edges by the distortion can be neglected.

On the other hand, some measurement errors may occur due to misalignments of the optical system and wind turbine blade under test, and this is observed as a shift or displacement of images (intrados and extrados) one with respect to the other. However, these errors are corrected by means of coordinate transformations in such way that is possible to reconstruct aerodynamic profile. The proposal presented compared with other methods has the advantage that the differences between the theoretical and the experimental profile are analyzed in an

**FIGURE 19** Drag ($C_d$) coefficients vs angle of attack ($\alpha$) for $Re = 5 \times 10^5$. A, Profile in P1, B, profile in P2 and C, P3.
FIGURE 20  Ratio $C_l/C_d$ coefficients vs angle of attack ($\alpha$) for $Re = 5 \times 10^5$. A, profile in $P_1$, B, profile in $P_2$ and C, $P_3$.
experimental way, with a high sensitivity, as well as being able to enter the point cloud to the Xfoil software for the aerodynamic analysis. The processing time and obtaining results are relatively fast once the calibration curve is available.

We can conclude that the manufacture of the blade and more if it is an open mold as the shovel is being studied is an important process that is reflected in the behavior of the aerodynamic coefficients, so the correct reproduction of the geometry must be guaranteed. As it could be observed in the three positions selected in the shovel under study, they had an error in the geometry with respect to the original profile used in the design, and this resulted in a reduction in the lift coefficient, the efficiency of the profile, and an increase in the drag coefficient, all this has consequences in the production of the wind turbine, as well as in the structural stability of the rotor.

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