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Comparison between Two Methods of Optical Profilometry on Micro-PTC

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Abstract. The development of a new prototype of micro-PTC (Parabolic Trough Collector) system requests to study the optical characteristics of the mirrors in use. Two techniques were developed for this purpose. The first one is based on the projection of a Moiré pattern on the mirror surface covered with an opaque material. It provides a reconstruction of the profile from which it is possible to calculate focus position, vertex position and hence the focal length. This method represents a very fast estimation of the macroscopic defects of parabolic collectors, which is useful to determine the quality of the product. The second method is based on the analysis of the reflection of a laser beam, scanning the surface of the parabolic mirror. Despite this latter method is more time consuming, it is a more accurate technique that allows measuring both position and slope of each point of the mirror. In addition, this second method permits to estimate the intercept factor of the concentrator.

INTRODUCTION

The transformation of solar energy into other forms leads inevitable losses in the process. One of the research objectives is to minimize these losses in order to obtain cheaper and more efficient systems to produce energy. In systems with CSP (Concentrating Solar Power) technology, solar energy is concentrated by mirrors in small areas to reach high temperatures for electricity production and other purposes.

A typical approach to the study of optical losses consists in treating optical errors and imperfections as independent and random processes, which are mathematically represented by a Gaussian distribution [1]. However, this approach is possible averaging the errors on a large number of collectors and would not be valid for small-scale systems.

Considering a single solar concentrator, an important parameter that estimates optical losses is the optical efficiency (η_{opt}) of the concentrator, namely the fraction of the solar energy that the mirror is able to send to the thermo-vector fluid. In this estimation, there are several factors to be evaluated: the reflectivity of the mirror (ρ); the absorbance of the receiver (α); the transmittance of the glass that protects the receiver (τ) and the intercept factor (γ), defined as the fraction of the solar rays reflected from the mirror to the receiver. The optical efficiency is expressed by the simple formula [2]:

$$\eta_{opt} = \rho \cdot \alpha \cdot \tau \cdot \gamma \tag{1}$$

The value of the first three parameters depends mostly on the quality of the materials used in the system and generally it is not very different from the design value given by the manufacturer. So the design values of these parameters could be easily used for the preliminary calculation needed in the planning phase of the system. Only the choice of the materials affects the optical efficiency of the design. Quality controls after production are also due on each component, but this aspect is outside the scope of this paper.

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A different scenario opens up about the estimate of the γ -factor. Considering, for example, a mirror with parabolic shape, the geometry tells that, for a proper alignment to the sun's rays, all the rays should be concentrated in a spatial point, namely the focus of the system. By the definition of γ it can be concluded that its design value will be one.

Despite this ideal condition, there are several issues affecting the real value of γ [2]: i.e. physical position of the receiver with respect to the mirror, actual geometrical shape of the concentrator and alignment of the system with respect to the sun. The last issue is due to the precision of the sun tracking system, but the other two are strictly connected with the mechanical manufacture of the concentrator. Therefore, it is very important to take them into account in order to calculate the real optical efficiency of each mirror produced. Besides, their consideration could be useful also to solve mechanical issues that systematically can affect the mirror shape and hence the efficiency of the system. For these reasons, an accurate study of the concentrator profile is necessary both in the design phase of new collectors and in their production phase.

Optical profilometry can be applied as technique used for the reconstruction of the real shape (profile) of industrial objects without the use of contact measurement devices. Several techniques of optical profilometry on CSP concentrators have been developed in recent years, in order to achieve a precise calculation of the optical efficiency of the system.

There are techniques based on photogrammetry [3], on deflectometry [4], on laser-reflection [5-7] and on the image reflection of the receiver tube [8-11].

However, these techniques need to be adapted for each concentrator, which can be different in shape and have peculiar dimensions. They may even fail for specific mirrors.

The development of a new prototype of solar concentrator requested to study and experiment specific techniques of profilometry. The examined concentrator is micro-PTC (Parabolic Trough Collector) and it is described in the next section. Then, the successive sections will present two methods of optical profilometry especially developed for this micro-PTC and tested on a collector prototype.

A NEW MICRO-PTC SYSTEM

A new prototype of micro-PTC system was developed at the University of Florence. It is characterized by mirrors of very small dimensions compared to PTC concentrators used in solar power plant operating all over the world. Figure 1 shows a scheme of the collectors used in this project. This system has a mirror (M-PTC-01) with an aperture of about 50 cm, while a typical operating PTC concentrator has an aperture of about 6 m.

This research project is intended to test the dimension scalability of the PTC technology. Its aim is to make possible to produce thermal energy and electricity directly on the consumption field, for industrial and residential purposes.

The particular optical design gives to the mirror the peculiarity of having a rim-angle (φ) (highlighted in red in Fig. 1) larger than 90°: in practice, the concentrator profile is a parabola with the focus under the mirror aperture.

The small dimensions of the collector made its accuracy of shape more sensitive for the calculation of efficiency. In fact, considering a defect of the same size on the surface of a micro-PTC collector and of a conventional-PTC mirror, it will result in a greater loss of energy on the smaller concentrator, because it affects a larger fraction of the total area of the receiver.

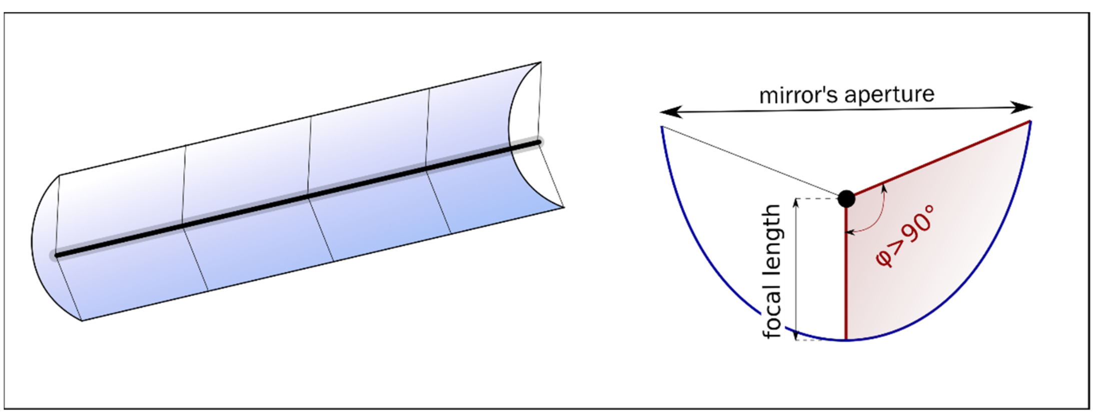

FIGURE 1. Scheme of the concentrating mirror M-PTC-01. The rim-angle is highlighted in red.

In order to realize a quality control for prototypes of this kind of reflectors, two methods of optical profilometry were developed. The first one is based on the Moiré technique, projecting a grating pattern on the mirror covered by a white opaque layer and successively analysing the image captured by a camera. The second method utilises a laser beam to scan the collector surface, acquiring by a camera the image of the beam reflected from the mirror.

MOIRÉ PATTERN PROJECTION ON OPAQUE COVERING

The first technique proposed is based on the concept of structured light profilometry [12]. A Moiré pattern is a pattern made alternating black and white straight lines. It is usually utilized for the so called Moiré interferometry [13], but a more simple and easy approach was experimented in this work.

The projection of a pattern of lines on the reflecting surface is a consolidated technique used in optical profilometry of solar collectors [4], and it is called deflectometry. Typically in this technique the reflected pattern is intercepted by a target: irregularities on the mirror surface can be seen as irregularities on image of the pattern reflected on the target.

It would be very hard to apply deflectometry on the M-PTC-01 concentrator. This is because of the particular rim-angle of these linear parabolic mirrors, greater than 90°, which means that the focus is positioned inside the mirror volume.

In order to afford a study of the mirror shape without any effect of spurious reflection, the mirror surface is covered by a white opaque material. A white flat reference plane (RP) is placed in front of the mirror sample (SA). The Moiré pattern is projected on both of them, while a DSLR (Digital Single Lens Reflex) Camera is placed in order to capture images of the projected pattern. Figure 2 shows a scheme of the experimental setup used for the application of this technique on a sample of micro-PTC. The projector is placed 3.73 m above the ground, whereas the parabola is placed vertically on a rack (Fig 2 (b)).

As the figure shows, the projected lines are perpendicular to the linear axis of the parabolic trough collector (vertical axis). As expected, a picture of the reference plane shows perfectly straight lines; whereas a picture of the mirror sample is characterized by the presence of parabolic shaped lines (sketched in Fig 2). A suitable Python code routine makes possible to identify the central pixel of each black and white line and to perform all the further calculations.

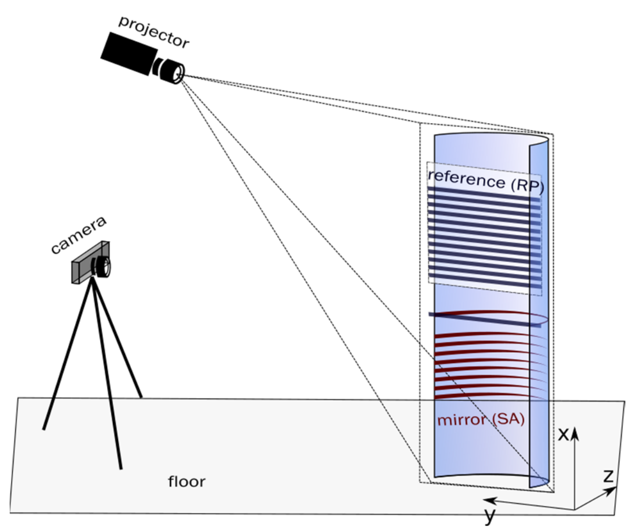

FIGURE 2. Experimental scheme for Moiré pattern technique.

In a simple approximation, the projector can be seen as a point from which all the luminous rays start and propagate diverging. Figure 3 gives a sketch of this simplified scheme with a suitable coordinate reference system.

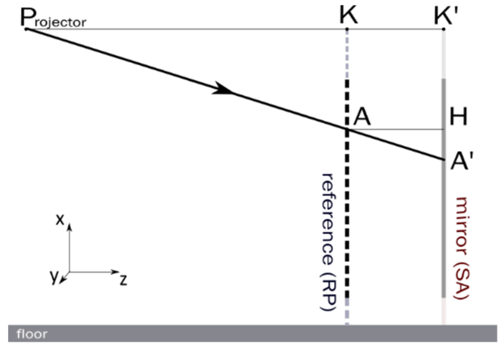

FIGURE 3. Simplified scheme of the geometry of the light rays emitted by the projector.

With reference to Fig. 3, considering every ray emerging from the projector (PK in the example shown), it firstly impinges on RP in the point A and then on SA in the point A'. Identifying each single line projected on both surfaces, it is possible to measure, for each y-position, the distance between the two lines (A'H), that is the distance between the point A' and the projection of A on the mirror surface, identified by H. Neither parallax error, due to the divergence of the camera objective, nor any optical aberration and deformations are considered.

In Fig. 3 the z-position of each point of SA is represented by the AH segment in the figure. For the similitude of triangles PKA and AHA' the following relation can be written:

$$AH = PK \cdot \frac{A'H}{AK} \tag{2}$$

Equation (2) is not able to give the proper 3D-profile reconstruction of the sample because it comes from an oversimplified sketch of the experiment; however, it suggests a couple of information. Firstly, the z-position of the points has to be proportional to A'H, namely the deformation (δ) of the Moiré pattern lines impinging the parabolic SA surface, secondly it has to be proportional to the inverse of AK, which is the x-position of the Moiré pattern in RP (x_{RP}). The origin of this coordinate reference system is placed on RP at the projector height. Both δ and x_{RP} can be measured in photos obtaining a value in the pixel space. Equation (2) can be written as:

$$z(x, y) = C \cdot \frac{\delta(x, y)}{x_{RP}(x, y)} \tag{3}$$

where C is an opportune constant, giving also the suitable pixel-mm conversion.

By the way, if one tries to make a reconstruction of the profile based on this formula the result is that z has a linear behaviour with respect to x with an angular coefficient that varies along the y-axis. This error can be removed simply correcting the formula with a linear term:

$$z(x, y) = C \cdot \left[\frac{\delta(x, y)}{x_{RP}(x, y)} - a(y) \cdot x \right] \tag{4}$$

where $a(y)$ is the angular coefficient resulting from a linear fit of the function $z(x)$ in the first, wrong, reconstruction.

A reference surface was tested in order to validate this procedure.

It is now possible to reconstruct the mirror profile, as shown in Figure 4 (a). Starting from these data, parabolic fits for $z(y)$ are performed for each x-position, obtaining vertex position, focal length and focus position. The results are shown in Figure 4 (b) and they give a value of (86.9 ± 0.3) mm for the focal length. This value is about 1 mm away from the design value, but, because of the width of the tube, this difference does not affect the value of the intercept factor. It is also worth to notice a little step occurring around $x = -2550$ mm. It is due to a manufacture defect at the conjunction of two modules composing the mirror, visible also to the naked eye.

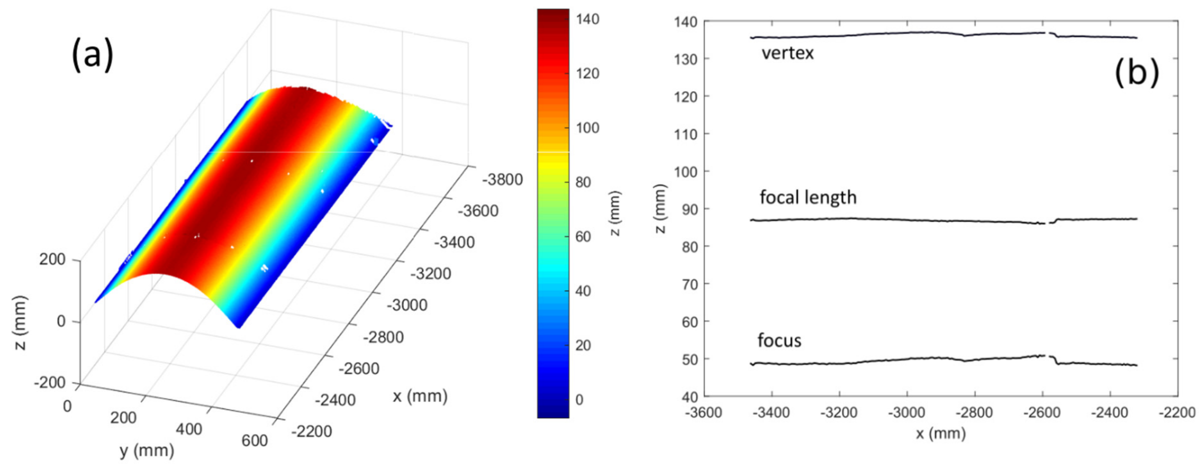

FIGURE 4. (a) Profile reconstruction of the parabola performed using Eq. (4). (b) Trend of vertex-position, focus-position and focal length along the x-direction.

LASER SCANNING ON THE REFLECTING SURFACE

The second technique that studies the profile of micro-PTC is based on the reflection of a laser beam on the reflecting surface of the concentrator. It is a well-known method already used to test the quality of solar concentrators [5-7]. The laser is displaced on a plane parallel to the aperture of the parabolic mirror and the laser beam impinges on the mirror with a direction perpendicularly to the aperture plane. For an ideal linear parabolic concentrator, with no defects on the surface, every ray of the laser beam would be reflected exactly on the focal line. On the contrary, in a real situation, the rays could be deviated with respect to the focal line, so a target is placed on this line, in order to measure the deviations from the ideal situation. Usually [5], the target is placed parallel to the mirror aperture, but for this concentrator, the target is tilted of an angle (α) of $38.5°$ with respect to the mirror aperture. Figure 5 shows the experimental scheme used for this method. With this configuration, the direction of the normal to the target surface is aligned with the bisector of the rim-angle.

Because of the parabola's rim angle, it is impossible to perform this technique with the target parallel to the mirror aperture, as used in previous studies [5].

The laser is shifted using automated translation stages, with high stability and very high precision of placement. These two translation stages move the laser diode along the x-y axes shown in Fig. 5.

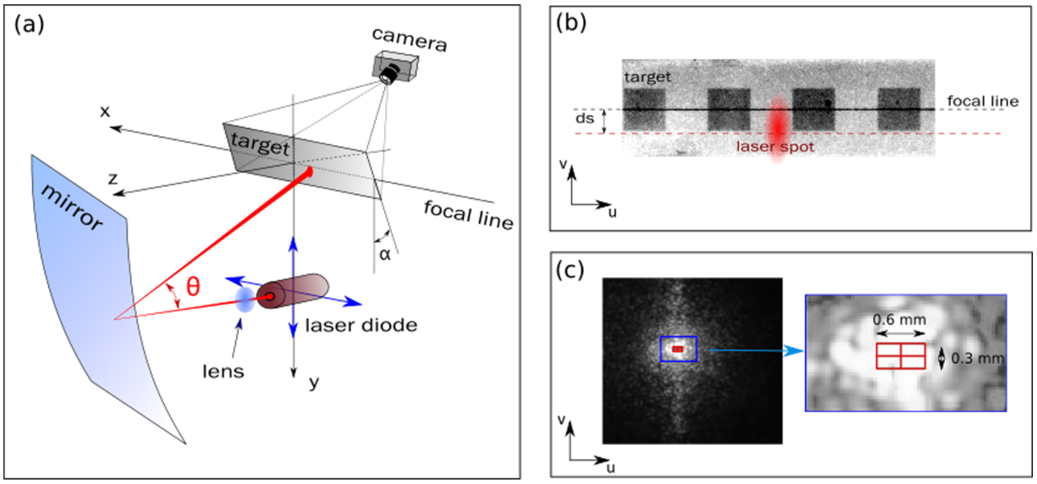

FIGURE 5. (a) Experimental scheme of the laser scanning technique. (b) Picture of the target in use for this experiment. (c) Picture of the laser spot impinging the target.

A camera acquires the target pictures (Fig 5 (b)), allowing to measure the position of the reflected spot (ds) with respect to the focal line. On the target a straight line is drawn, placed on the focal line, and a series of squares with a side of 1 cm. The presence of these squares, with a distance of 1 cm each from the next, allows a correct calibration of the camera that converts the pixels in mm.

For the purpose of image-recognition of the laser spot on the target, a new method was developed. The previous studies [5-6] usually utilize a centroid-recognition tool to calculate the central position of the spot reflected on the target. However, these tools do not allow to calculate the uncertainty of measurement, whose value is decisive in the calculation of the final accuracy of the profilometry.

A converging lens is placed in front of the laser, so a de-focused image of the spot is produced on the target. With an appropriate alignment between the laser and the lens, the intensity maximum of the acquired image refers to the rays of interest for the reconstruction.

To find the maximum of intensity of the image, considering a proper system of coordinate (u, v) (Fig. 5 (c)) the following procedure was developed:

1. the information about the intensity of the light (I_{spot}) diffused by the target is elaborated;
2. for each row of pixels, namely each v-position, I_{spot} is fit with a Lorentz-like function, expressed by the formula:

$$I_{spot}^{fit}(u) = \frac{p_1}{(p_2 - u)^2 + p_3} + p_4 \tag{5}$$

   where p_1 , p_2 , p_3 and p_4 are the parameters of the fit;
3. the u-coordinate ($u_{\max}^{fit}$) of the maximum of u_{spot}^{fit} is calculated;
4. the mean value of $u_{\max}^{fit}(v)$ represents the u-position of the searched point (u_{spot}), while its standard deviation is kept as its uncertainty;
5. the same procedure exposed in 2-4 is applied for each column of pixels, giving the value (v_{spot}) and uncertainty of v-position.

Typical values of uncertainty are 0.3 mm for the u-direction and 0.15 mm for the v-direction (Fig 5 (c)). Finally, knowing the v-pixel-position of the focal line it is easy to determine the value of ds s as the difference between this one and the v-position of the spot center. It is worth to note that only v-position is useful for this scope.

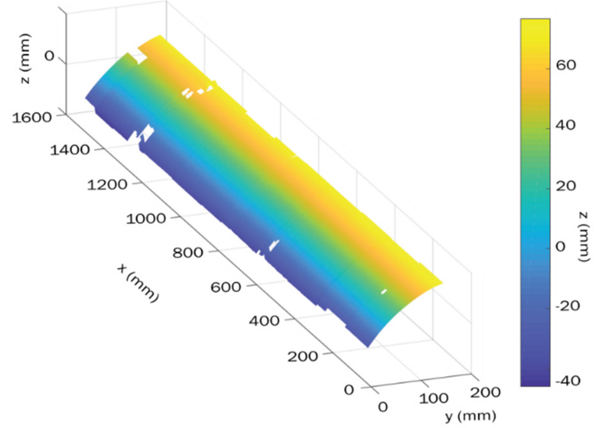

FIGURE 6. Profile reconstruction of the semi-parabola performed with the laser-beam method. The colour scale indicates the amount of z.

In fact, the reflection of a light ray depends not only on the spatial coordinates of the mirror, but also on the slope of the reflective surface. Considering only the position of the ray on the target, several values of coordinates and slope let the ray impinge on the target in that location. On the other hand, knowing either coordinate or slopes, with a simple geometric calculation it is possible to obtain the other value.

Starting from a point, measured with a contact-profilometer, the successive points are calculated using an iterative procedure [5,6]. The parameters obtained are coordinates and slope.

It is out of the scope of this paper the discussion about all the calculations of the method. They are made by a system of equations, solved numerically. After the calculation, it is possible to know the coordinates of every point of the scanned surface, and so a profile reconstruction is possible (Figure 6).

From the knowledge of coordinates and slope, it is possible to deduce, for each point, if the light impinging will reach the absorber or not. The fraction of "good" points with respect to the total scanned surface can give an estimation of the intercept factor. For this mirror the obtained value was $\gamma = 0.91$.

CONCLUSIONS

Profilometry measurements are useful to detect surface faults on solar concentrators especially for linear parabolic mirrors, which can be imperfectly manufactured. Adapting the procedure to the specific shape and size of each reflector, optical profilometry techniques can be applied on PTCs (parabolic trough collectors) to reconstruct the real profile of the mirror.

These methods have been applied to a new prototype of micro-PTC, characterized by small sizes and elevated curvature of the parabolic mirror (focus under the mirror aperture). The peculiar dimensions and shape of this micro-PTC did not allow to perform a simple deflectometry and made necessary to re-adapt the well consolidated laser-reflection technique.

The results of this experimentation on the micro-PTC are two methods of optical profilometry customized for the micro-PTC and tested on a collector prototype.

The first technique allows a fast analysis of the parabolic mirror shape; it reconstructs the mirror profile and calculates the focal length for each parabolic section. Once calibrated a reference plane, it is possible to repeat the measure for each produced micro-PTC, giving a very quick estimation of macroscopic defects. This feature makes this method a good candidate for quality control on solar collector production.

The second method relies on laser-reflection and follows an existing method [5-7]. However, the micro-PTC shape made necessary a modification of the experimental setup, with the tilt of the target position. This technique, differently from the first one proposed, although it is more expensive in terms of time, gives more information about the quality of the concentrator. Starting from an accurate profile reconstruction and slope error calculation, it gives an estimate of the intercept factor for every point in the mirror. This permits both a fine-control on the manufacture of the parabolic mirror and an accurate calculation of the optical efficiency for every mirror produced. Furthermore, in the actual phase of test for the micro-PTC prototypes it is very important to calculate this parameter: with this number is easier to separate optical losses from other energy losses, allowing to study and improve each aspect of this micro-PTC system under development.

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