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Mirror surface check on solar troughs by optical profilometry

P. Sansoni[1], D. Fontani[1*], L. Mercatelli[1], D. Jafrancesco[1], E. Sani[1], S. Coraggia[1],
M. Meucci[1], L. Marconi[1], S. Toccafondi[2]

*[1] CNR-INO National Institute of Optics, Largo E. Fermi, 6 – Firenze - 50125 - Italy- Phone. +39-055-23081; Fax. +39-055-2337755; Email: *daniela.fontani@ino.it ; paola.sansoni@ino.it;*
[2]Energetic Dept. of Engineering, Univ. of Florence, Via Santa Marta, 3 - 50139 Firenze - Italy Phone: +39-055 4796 331; Fax: +39-055 4796 342

Abstract

Linear parabolic collectors usually need profilometric control since the reflector surface can be imperfectly manufactured. Optical profile assessment is generally addressed to detect small localised defects. The paper proposes two optical devices that were developed simulating profile measurements on linear parabolic mirrors. Solar troughs are employed in thermal plants and concentrating photovoltaic systems. The profilometer examines the reflector surface operating on a plane transversal to the linear axis of the trough collector. Then the detection is repeated displacing the optical device along the linear collector axis. The first profilometer includes a shifted laser source and a target placed at the collector focal distance. The second profilometer has a fixed target and a linear laser source, which is approximately located in the focal position of the solar mirror. Ray-tracing simulations and practical tests are illustrated for both optical devices.

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Keywords: profilometry; optical metrology; mirror surface.

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1. Surface imperfections of linear concentrating mirrors

The possibilities of surface defects arising in the realisation of concentrating mirrors were studied while developing the prototype of a solar troughs plant. Linear solar mirrors of parabolic profile were experimented for thermal and concentrating photovoltaic applications. Some linear mirrors of the plant

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* Corresponding author. Daniela Fontani Tel.: +39-055-23081; Fax: +39-055-2337755.
E-mail address: daniela.fontani@ino.it

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prototype collected the sunlight over a metal pipe surrounded by a glass tube. Other linear parabolic mirrors were coupled to a line of concentration photovoltaic cells (CPV systems).

The practical experimentation on real solar mirrors evidenced that they are typically affected by several types of surface defects. The main categories of defects for solar troughs are: rigid deformation, local imperfection and torsion effects. The defects were reproduced by suitable mathematical models performing energetic and angular analyses by means of ray tracing simulations.

Trough collectors frequently present a rigid deformation of the parabolic profile, almost uniformly distributed along the linear axis of the trough. A previous work [1,2] proposed an innovative approach to reproduce the rigid deformations of the linear parabolic mirror. The methodology to simulate mirror deformations employs conic constant K and conic equation to represent the mirror profiles. The deformation can be of two types: elliptic, for $-1 < K < 0$ or hyperbolic for $K < -1$. While for $K = -1$ the conic equation represents a parabolic profile. This procedure to replicate the deformations of a parabolic mirror is simple and efficient. However the most interesting result is that it seems to reproduce the imperfect rigidity and the flexibility of a real solar collector. The main consequences of these rigid deformations are reduction of collection performances and acceptance angle, representing the tilt angle in which the collection efficiency keeps its maximum value. The acceptance angle depends on the respective positions of mirror and absorber; consequently it is strongly affected by mirror deformations and it also depends on the collector features.

Small local imperfections can often occur on the reflecting surface. These defects are associated to particular types of mirrors surfaces and specific manufacturing methods to realise the collecting mirrors. Several types of reflecting surfaces were experimented in our test plant [2]: M1) optical glass aluminized on the back face; M2a) metallic reflecting surface obtained gluing a thin layer of metal sheet over the opaque support; M2b) metal mirror obtained curving an aluminium plate with an optically worked surface. Glass mirrors M1 perform higher reflection, having a more uniform surface with respect to metal mirrors M2a. The drawbacks of M1 are fragility and higher cost in comparison to M2a. A trade-off between M1 and M2a is represented by the metallic reflecting surface M2b. The behaviour of the glass mirror M1 is similar to the metal mirror M2b: both are mainly affected by rigid deformations. The metallic reflecting surface M2a is characterised by local imperfections and the proposed profilometers are addressed to analyse this type of surface defects. For M2a the metallic reflecting surface is realised by a mosaic of 6 sheets in one module or with a mosaic of 12 sheets in another module. Various processes of deposition and gluing were tested. Typically local modifications of the correct parabolic curvature appear on the M2a surface and the total reflection decreases; but improving the deposition uniformity and reducing the size of the sheets the defects can be limited.

Finally the whole structure of solar trough can experience a torsion effect mainly caused by the mechanical support. The effects of a mechanical torsion are analogous to the misalignment of the parabolic mirror axis with respect to the North-South direction [2, 3]. The focused image appears tilted with respect to the linear absorber.

2. Optical profilometry on linear mirrors

The profile control on real mirrors of solar troughs is fundamental since the reflecting surface can be imperfect. The discussed profile measurements are addressed to detect small localised faults. The optical methodologies employed to reveal profile defects are mostly based on techniques of geometrical optics [4-6]. Starting from the identification of the position of a luminous ray impinging in a specific point of the mirror, we verify that the reflected ray is deviated in agreement with the value of the local surface slope. Some methods described in literature [7] are extremely time-consuming because they refer to point detections, obtained by scanning the reflector surface. The drawback is that the time necessary to complete the measurement increases as the requested resolution improves.

To avoid this problem, we can utilise image processing techniques that allow analysing, in a reasonably short time, the entire mirror surface. The methods that employ this approach examine, from a distant point, the image of the linear absorber that is generated by the solar linear reflector. This optical configuration corresponds to observe an object, the absorber, through an optical system, the reflector, in magnification conditions. If the observation distance exceeds the mirror focal distance, the image visible from faraway covers the whole reflector and the observer sees a uniformly coloured image. Possible irregularities of mirror profile subtract information to the image in the defective points, which thus appear as zones of different intensity within the image [8-11]. Other procedures refer to the analysis of a calibrated mask, whose image is reproduced by the concentrator [12-14]. Our research group developed a method using a coloured pattern, projected on a screen through the concentrator [15]. An alternative approach exploits photogrammetric techniques [16]. A 3D-recontruction of the examined reflecting surface can be obtained elaborating the detected image. Within the grating image reflected by the mirror surface, the deformed lines indicate slope variations. These defects can be extracted from the image using structured light techniques [17-20] adapted to the specific case. The adaptation consists in applying structured light procedures on reflectors, while they are typically used on diffusing surfaces [21]. Some recent researches include a method of like fringe reflection [22-24] and a 3D optical profilometry technique [25].

In general a local surface fault can cause significant energy losses even for few millimetres of high over the parabolic profile. The effect of local defects strongly depends on size and shape of the absorber and obviously on the collection geometry. The need of defining a practically applicable procedure to measure superficial irregularities of solar reflectors suggested starting our research with some preliminary theoretical studies. On the base of these analyses various techniques of optical profilometry are under development on a parabolic troughs plant prototype for solar tests [2]. The aim is to obtain simple, compact, easy-manageable and cheap profilometers.

The paper proposes two optical profilometers for solar reflecting surfaces, which were studied simulating profile measurements on a linear parabolic mirror. The profilometer examines the mirror surface operating on a plane transversal to the linear axis of the solar trough. Then the detection is repeated relocating the profilometer along the linear collector axis.

The “shifting source profilometer” (optical profilometer OP1) realises a source of parallel rays and the target is simply placed at the focal distance of the examined collector. The source can be a semi-conductor laser shifted in the direction perpendicular to the beam axis. This laser is displaced along the collector aperture scanning the whole mirror aperture.

The “linear source profilometer” (optical profilometer OP2) includes a linear source and a fixed target. In alternative the source can be realised by a semi-conductor laser, which rotates over a suitable angle to cover the mirror surface under examination. Both source and target are approximately located on the axis of the collecting mirror. The target should have appropriate dimensions to receive all reflected rays.

Both profilometers are compact, simple and cheap to be realised and they provide rapid results. However their most appealing advantages are simplicity of working principle and facility of measurement alignment.

3. Working principle of profilometer OP1

The first proposed optical profilometer has as main components a shifted laser source and a fixed target. It is denominated OP1 for “Optical Profilometer 1”.

Optical profilometer OP1 exploits the geometrical property of the parabolic reflector, which concentrates in its focus the luminous rays impinging perpendicularly to the entrance aperture. The parallel luminous rays are simulated by laser beams emitted by a source shifted using a motorised translation. The beams reflected from each position of the shifted source then reach a screen. The displacements from the theoretical positions of reflections are measurable on the screen. From these data it is possible to estimate the amount of surface deformation. The device OP1 requires complex and quite precise mechanical systems.

The working principle of OP1 is illustrated in Figure 1: the source emits parallel rays that are reflected by the examined portion of mirror surface and they successively impinge on a target placed near the parabolic collector focus.

Figures 1, 2, 4, 5 were obtained using the Zemax ray tracing software. Figure 1 shows how the parallel rays (of the shifted laser) are reflected by a linear parabolic mirror surface containing a local imperfection.

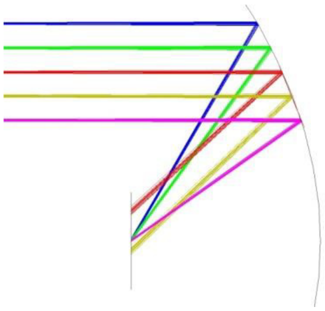


Fig.1 – Ray tracing simulation of OP1.

Where the mirror has the perfect parabolic profile the rays are concentrated in the focal point and they produce the focused image of Fig.2a. Where the mirror surface presents curvature variations, as in correspondent of a local fault, the rays are reflected out of the focal point and they create the defocused image in Fig.2b.

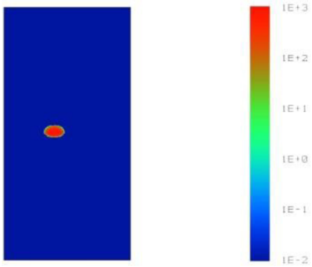


Fig2a – OP1 image for a perfect parabolic mirror.

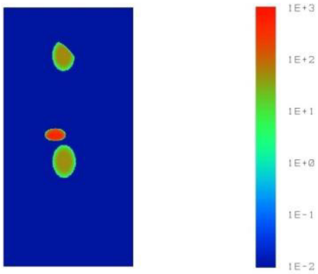


Fig2b – OP1 image for a defective mirror portion.

4. Practical results for profilometer OP1

The profilometer should test solar linear mirrors examining the reflecting surface along the linear parabolic collector axis. In practice the optical layout of the detection system cannot work exactly on a plane transversal to the solar trough axis. Hence the target must be slightly displaced with respect to the plane of parallel rays. This arrangement allows the rays to reach the central part of the tested reflector, otherwise shaded by the target (vignetting effect).

The practical realization of OP1 needs a double axes shifting system, because typically the mirror transversal width is much larger than the array source dimension.

A simplified practical realisation of profilometer OP1, using a single laser ray, is presented in Fig. 3. The photo shows the target in case of a detection on a defective surface. When OP1 examines a perfectly parabolic mirror surface, on the target there is only the central laser spot in the focal point, indicated as F. When OP1 observes a local imperfection on a defective mirror, on the target the laser spot appears displaced and enlarged, as shown on the upper corner of the Fig. 3. The picture also reports the length of 1 mm for a visual estimation of the displaced spot extent.

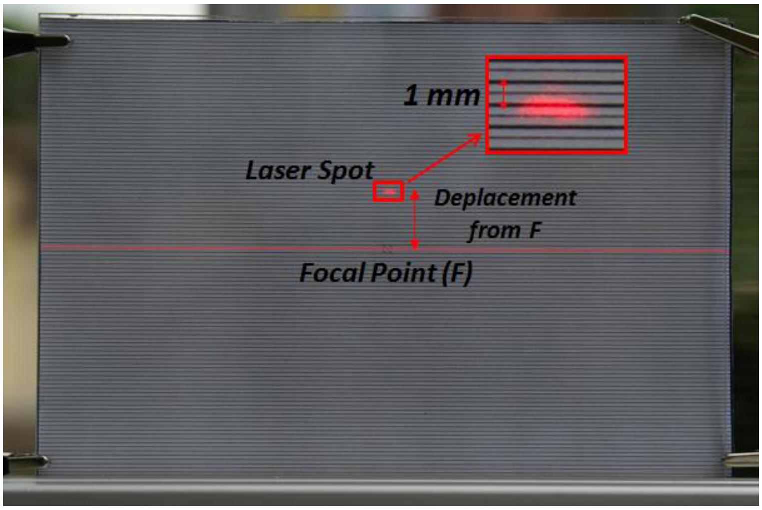


Fig.3. Photo of a practical realisation of OP1: defective mirror detection.

5. Working principle of Profilometer OP2

The second proposed optical profilometer has as main elements a linear source (or a rotating point source) and a fixed target. It is denominated OP2 for “Optical Profilometer 2”.

The working principle is based on the formation of the image of a source point, which is observed through the reflector under test. In order to minimise the space between source and screen, their distance from the reflector should correspond to the value of 2f, where f is the focal length of the parabola.

Optical configuration and working principle of OP2 are more complex than those of profilometer OP1. Source and target are placed on the symmetry axis of the parabola (profile of the solar mirror), but at different distances. Figures 4-5 present the working principle: the rays emitted by the rotating laser are reflected by the surface of the linear collector and they arrive on the fixed target.

In practice OP2 is composed of a linear source and a fixed target: the target should be placed at the parabola focal distance (f), while the source can be located at a about a distance of 2f on the symmetry axis of the parabola, as Fig. 4 shows.

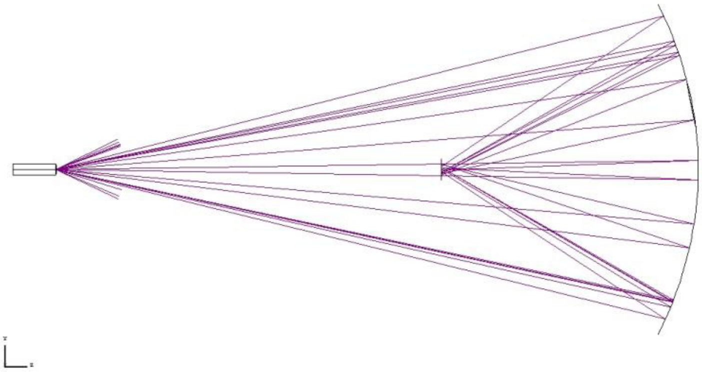
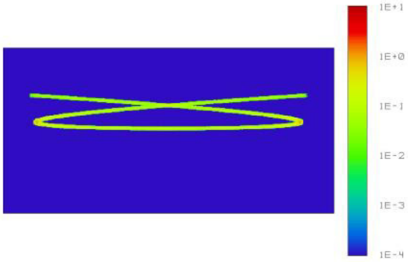


Fig.4 – Ray tracing simulation of OP2: side view.

The image obtained in case of a perfect parabolic mirror is shown in Fig.5a: the reflected light creates a “γ” form. This is due to the fact that source and target are not in the same plane transversal to collector axis. For practical reasons the target is slightly displaced along the trough axis with respect to the source. The image would be a line in case of perfect axial coincidence of source and target.

Fig.5b reports the image generated by a defective mirror portion: the “γ” form presents a discontinuity and the light subtracted to the “γ” form appears as a line out of the “γ” form.



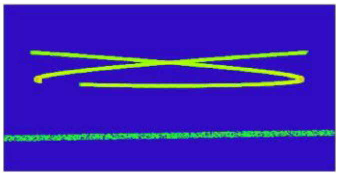


Fig.5a – OP2 image for a perfect mirror.

Fig.5b – OP2 image for a defective mirror portion.

6. Practical results for profilometer OP2

For most applications of optical profilometer OP2 it is sufficient to use the projection of a diverging light line; so the sample can be statically illuminated avoiding the use of scans.

Some detection examples are reported in Fig. 6. The three pictures of Fig. 6 present the image, with its characteristic "γ" form, obtained with and without surface defect. When OP2 analyses a perfectly parabolic mirror, the resulting image is a complete and continuous "γ"-image, as shown in the top photo of Fig. 6. When OP2 examines a defective portion of the mirror, the "γ"-image presents some discontinuities, as shown on the two bottom photos in Fig. 6. Hence the experimental tests confirm that local imperfections subtract luminous points from the "γ"-image projected by the linear source. The luminous noise and the diffused light, due to micro-roughness of the parabolic surface, do not allow the individuation of the external line, corresponding to the subtracted light, which is visible only in the simulation of Fig. 5b.

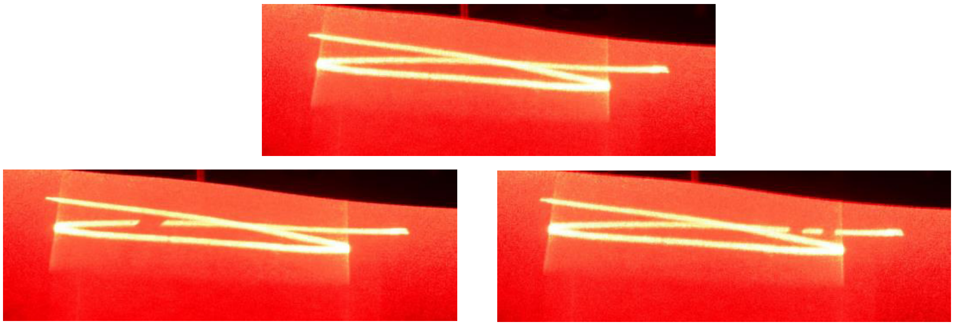


Fig.6. Photo of a practical realisation of OP2: faultless mirror detection (top) and two local defect mirror detections (bottom).

7. Conclusion

The need to assess acceptable values for the superficial irregularities of solar collecting mirrors suggested starting our research with some preliminary theoretical studies. Successively, on the base of these studies, various profilometry methods were developed to control the surface condition directly on the solar troughs plant. In particular the surface profilometers were studied to examine linear parabolic reflectors used as solar collectors.

Considering that a linear parabolic mirror can have an aperture of one or two meters and a length of several meters, it is preferable to use simple and manageable profilometers. Therefore the measurement apparatus was studied to be light, easily transportable and with an extreme facility of alignment. The paper presents two optical profilometers with these advantageous characteristics. Both optical systems are conceived to examine only a transversal section of the parabolic reflector. The profilometer must be placed in the region to be measured; then it is eventually displaced along the linear axis of the solar trough to scan the whole mirror. In practice the optical layout of the detection system cannot work exactly on a plane transversal to the trough axis. Hence the target must be slightly displaced with respect to the source.

In both profilometers the local imperfection of the reflecting surface is detectable on the target image as spurious light: outside the focused image for the "shifting source profilometer" OP1 or outside the "γ" form for the "linear source profilometer" OP2.

Both optical systems are easy to be displaced and aligned, because source and receiver target are located quite near one to the other. In particular, in the "linear source profilometer" OP2 these two elements can be integrated and mounted on the same support, thus constituting a compact and portable component of the device. The two proposed profilometers can be adapted both for qualitative tests and for quantitative measurements, if appropriate systems to analyse the reflected beam are employed.

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