SOLAR TROUGH MIRROR SHAPE SPECIFICATIONS

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Abstract

The performance of concentrating solar collectors depends to a significant amount on the shape accuracy of the mirrors reflecting the sunlight onto the absorber. For the case of parabolic trough mirrors and on the basis of previous work on shape measurements and ray-tracing, a quality parameter has been defined, that quantifies the average deviation of the reflected beam from the design focal line. It could be demonstrated that application of standard distribution (Gauss distribution) is sufficiently related to derive the performance relevant intercept factor from it. As objective for the glass reflector for high performance trough collectors a typical value for the focus deviation RMS in transversal direction is about 15% of the absorber diameter.

Keywords: parabolic trough, mirror, intercept factor, optical efficiency, deflectometry, shape

1. Introduction

Parabolic trough collectors are the key component of current solar thermal power generation technologies. Their cylinder-parabolic reflector shape concentrates sunlight on a focal line in focal distance from the reflector. The absorber tube located at the focal line absorbs the incoming concentrated solar radiation and converts it into heat at typically 300-400°C. In order to reach high optical efficiency values the specular reflectance must by high and the parabolic shape of the reflector surface and the relative position of the absorber tube have to be quite accurate. This refers in particular to the slopes of the mirrors themselves. Due to the reflection of the light beam, slope deviations of mirrors have double the effect on the direction of reflected light rays. Reflector quality is usually evaluated in terms of standard deviation parameters of the reflector slope of the whole mirror element, separated in transversal (across the absorber tube axis) and longitudinal slope (along the absorber tube). Industry typically uses laser-beam intercept factors on the receiver size as reflector quality parameter.

The resulting laser intercept factor values of easily 99-100% (of laser beams on the absorber tube of 50-70 mm diameter for LS3/Eurotrough geometry) are not a useful figure to determine or specify the mirror quality because the real sunlight focused in a real collector has significantly larger beam spread and thus may result in a lower intercept factor than the ideally positioned laser beam. Obviously the distribution function of the beam deviations from the optimum geometry is relevant to further analyze the effect.

Measurement of the mirror slope deviation is usually performed with optical methods. Besides the direct measurement of the laser beam deviation on a target in the focal region, close range photogrammetry with high target marker density[1] as well as deflectometry or fringe reflection have been successfully applied. This last mentioned technique of deflectometry can lead to the best results in terms of resolution, accuracy and measurement speed. It has been used for the acquisition of data for this work and is described in more detail by Ulmer et al.[2, 3, 4].

2. Focus Deviation

In order to give a more general approach for specifying slope accuracy, it is proposed to evaluate the frequency distribution of the focus deviations of the reflected beams from the ideal focal line, named "focus deviation". This value is derived from the area-weighted results of the angular deviation of a reflected beam multiplied by the distance from mirror to focus on each of the measured surface elements on the mirror with the projected surface area a_i. This parameter is evaluated in both x and y (transversal and longitudinal) directions of the trough collector, *FDx* and *FDy* respectively.

$$FDx = \sqrt{\sum_{i=1}^{n}\left(FDx_i^{\,2} \cdot \frac{a_i}{A_{ges}}\right)} \quad \text{and} \quad FDy = \sqrt{\sum_{i=1}^{n}\left(FDy_i^{\,2} \cdot \frac{a_i}{A_{ges}}\right)}$$

FDx and *FDy* are related to the reflector slope, being *SD* approximately *FD* divided by double the average focal distance f_m for the mirror element.

$$SDx = \frac{FDx}{2f_m} \qquad f_m = \sum_{i=1}^{n}\left(f_i \cdot \frac{a_i}{A_{ges}}\right)$$

3. Measurement with Deflectometry

Deflectometry is a digital photographic measurement technology with image analysis of the reflected image of a pattern taken by a high resolution camera. Main advantage of deflectometry over other methods is the high spatial resolution and the fast measurement of the relevant mirror slope information. The technique is also applied in other fields of application of surface analysis in quality control. No preparation of the sample other than cleaning and positioning is required. Dimming of the surrounding light sources might be required for error-free measurements.

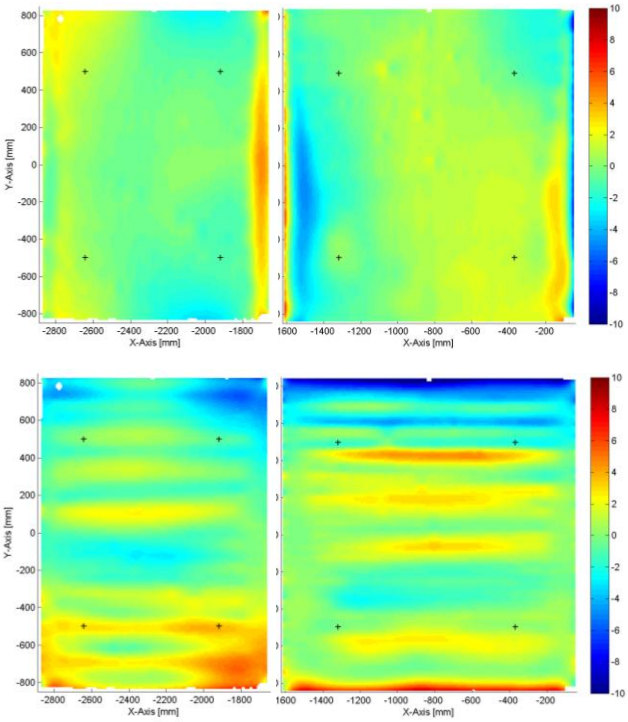

Figure 1: Example of a measurement result of the spatial distribution of the transversal (upper) and longitudinal (bottom) slope deviations for the surface analysis of a pair of RP3 mirrors, scale in mrad

Figure 1 shows an example of a measurement result for a pair of RP3 mirror panels (LS3/Eurotrough geometry). The described parameters and procedures in this paper can be applied to all types of trough geometries, although they are generally shown on exemplary RP3 mirror panels. A surface area of >98.5% of the mirror aperture area is evaluated. Previous measurements and definitions with e.g. 20 mm of disregarded boundary area exclude critical parts of the mirror from the assessment. The measurements are performed on the final product with reflective layer, but are also possible on uncoated glass during the production process and give the same results.

4. Statistical Analysis of the Slope Deviation Data in mrad

For each mirror panel the statistics of the slope deviations is analyzed in such way that the individual values for transversal and longitudinal orientations (x and y) are weighted with the respective mirror area projected into the aperture plane (orthogonal to the optical axis). For these area-weighted slope deviation results statistical parameters as average value, standard deviation value, root-mean-square (RMS) and the frequency distribution can be used for further analysis. Due to the alignment of the measurement set-up the average value is usually very close to 0. The relevant information is contained in the RMS, which in this case is very similar to the standard deviation of the slope deviation (named: *SD*) as it is a measure for the width of the distribution function of the shape deviations. Applying further statistical analysis, it can be expected that 68% of the relevant mirror surface has a slope deviation of less than *SD* from the average, and 95% has a slope deviation of less than 2 *SD* from the average. The example for the transversal deviation distribution of the same mirror as in Figure 1 is shown in Figure 2.

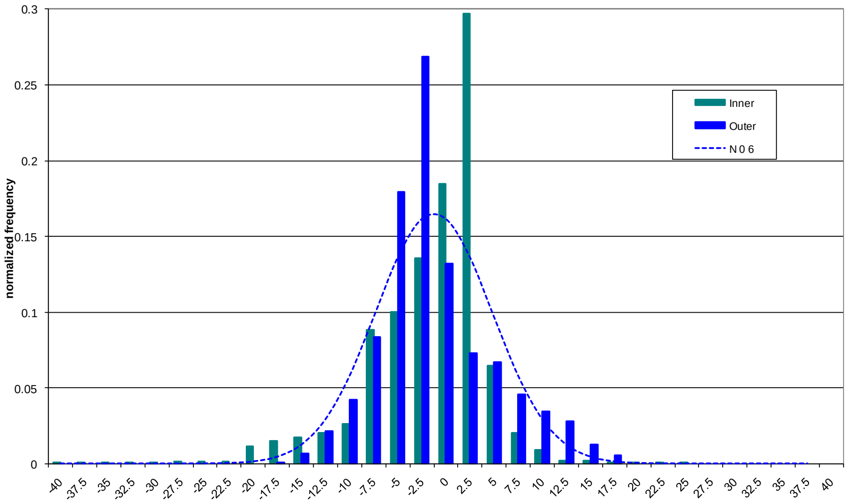

Figure 2: Example of a frequency distribution of the transversal focal deviation for the surface analysis of a pair of mirrors, scale in mm

5. Evaluation with Ray-Tracing

5.1. Focus Deviation in mm

The resulting mirror shape is further analyzed in a ray-tracing code to calculate the deviation of reflected beams from the given focal line. The calculation is based on the approach that the angular deviation of the surface slope in both transversal and longitudinal direction together with the distance of the individual mirror element from the focal line results in a deviation of a reflected (ideal) beam from the focus. The result is called the “focus deviation” in millimeters, and is also represented as map and statistical parameters of the mirror panels, but now taking into account the specific parabolic collector geometry. As before, due to the alignment of the measurement set-up the average value is usually very close to 0 mm. The relevant information is contained in the standard deviation of the focus deviation (named: *FD*) as it is a measure for the width of the distribution function of the light across the focal area. Applying further statistical analysis, it can be expected that 68% of the relevant mirror surface has a focus deviation of less than *FD* from the average, 95% has a focus deviation of less than 2 *FD* from the average, and 99.7% has a focus deviation of less than 3 *FD* from the average. An example for the transversal deviation is shown in the following Figure.

The resulting values in particular of the transversal focus deviation *FD* and the standard focus deviation *FDx* can be directly compared to the absorber tube radius in mm. The measurements have shown that the distribution of the focus deviation can be sufficiently approximated by a Gaussian standard distribution. It becomes obvious that 3 *FDx* should be lower than the absorber radius in order to reach the initially described high laser ray intercept factors of close to 100%. However, the statistical parameter *FD* is a much more reliable parameter for the description of the mirror shape accuracy than the laser intercept factor or other parameters.

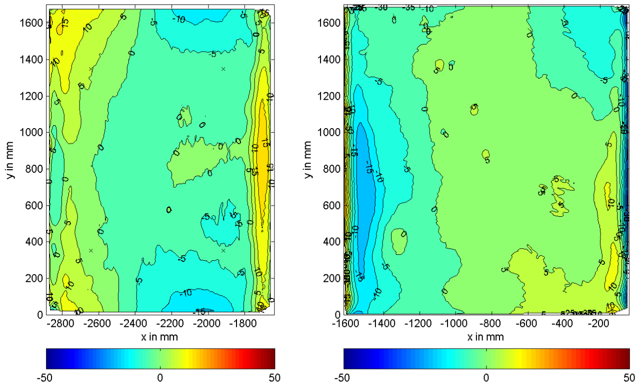

Figure 3: Example of a measurement result of the spatial distribution of the transversal focal deviation for the surface analysis of a pair of mirrors, for 0° incidence angle, scale in mm

5.2. Intercept Factor Calculation for Sunlight

In further ray-tracing analysis the effects of the sun shape (sun disk) and of further collector quality parameters are taken into account.

The sun shape used for the analysis is a universal sunshape[5] with a circumsolar ratio (CSR) of 3.5%. This corresponds to a typical sun shape with clear sky conditions.

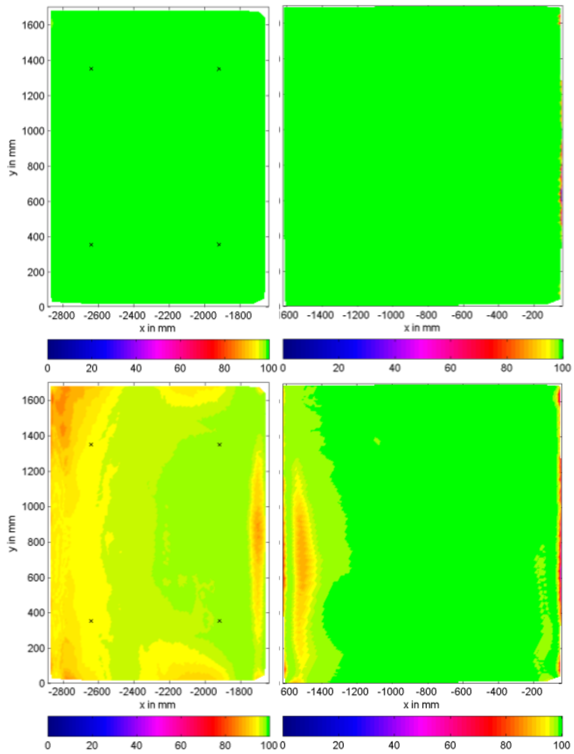

Figure 4: Example of a measurement result of the intercept factor distribution of a pair of mirrors for a pure sun disc (upper) and for a "degraded sun" (bottom) for 0°incidence angle, scale in %

Further slope deviations that occur in a real collector due to tracking errors, absorber tube alignment, structural shape errors and deformation under load in operating conditions (excluding sun shape and mirror shape effects) have been assumed from previous experience (e.g. Schiricke[6]) to about 4 - 6 mrad.

The relevant results from this ray-tracing study are the overall intercept factor for each individual mirror panel, and the map of local intercept factor values for the measured mirror area. An example is shown in the following figure for a "degraded sun" including both sunshape and collector deviations in an overall beam spread of 5.7 mrad.

The figures show the typical effects of mirror borders from hot-sagged mirror panels, in this case by the German manufacturer Flabeg GmbH. Deviations of the slope on the inner and outer rims of the mirror panels have a noticeable effect on the intercept factor. The effect is more important for the outer mirror panels, because the larger distance from the focal line together with the size of the image of the "degraded sun" becomes more relevant.

5.3. Discussion of the results

Ray-tracing analyses on measurement data from parabolic trough mirrors of different manufacturing qualities have shown that the standard focus deviation parameter *FDx* and the energy efficiency (measured as intercept factor) of a parabolic trough collector are closely related to each other. The following graph shows this relation for a "degraded sun" of 5.7 mrad. It includes mirrors of different manufacturers and bending technologies and thus also different patterns of shape characteristics.

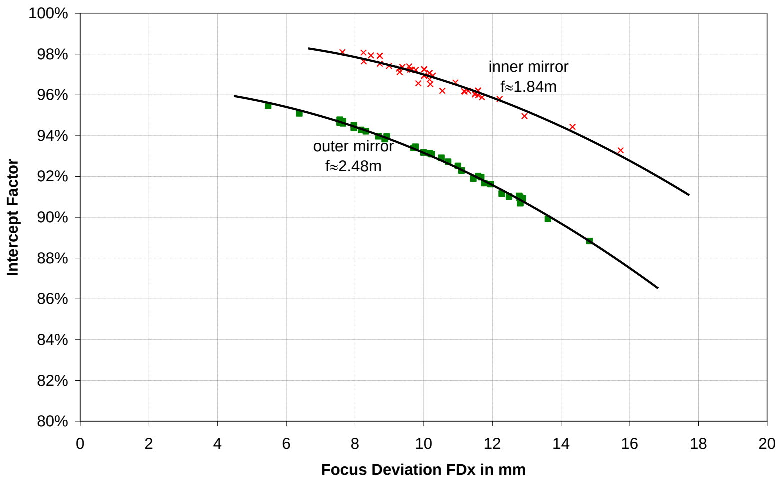

Figure 5: Intercept factor ray-tracing results for EuroTrough (RP3) mirror panels assuming a typical sun-shape and including typical tolerances for the rest of the collector components, for 0° incidence angle

The graph with the arbitrary fit line shows the consistency of the proposed mirror quality parameter *FDx* with the intercept factor and thus overall optical efficiency of a parabolic trough collector equipped with these mirrors of different manufacturing processes. For combining the intercept factor values of inner and outer mirror panels the weighting of the mirror aperture area for RP3 panels of 56% and 44% respectively is to be taken into account.

The graphs also reveal that the transversal contribution of the mirror slope (*FDx*) is the dominant effect. Longitudinal slope deviations (*FDy*) from manufacturing imperfections, visible as waviness or deformed borders on the curved boundaries have a much lower effect (in the range of 1:10). Its analysis takes typical annual variations of the incidence angle into account and is not in the scope of this paper.

As result from this work as well as current experience with EuroTrough collector production quality and sun shape considerations we propose a minimum criterion of the standard focus deviation of *FDx* of below 12 mm for the current RP3 panels with 1710 mm of focal length, 5776 mm of aperture width and 70 mm of absorber tube diameter. It should however be the goal of mirror manufacturing of reaching *FDx* values below 10 mm. Future production quality achievements of 8 mm or below, especially for the outer panels, bear the potential of an additional percentage point of increase in optical efficiency of the solar field, with relevant impact on overall economic performance of the solar power production with this technology.

6. Conclusion

Based on measurement results and ray-tracing analyses, and taking into account the large number of effects and influence factors, it is proposed to specify mirror shape quality with the transversal standard focus deviation parameter. The overall optical quality of a solar collector field is evaluated assuming normal distributions of the focus deviation frequency functions for the rest of the effects. The specification of the Standard Focus Deviation *FD* can replace previously used standard slope deviations and definitions related to laser-beam intercept factors on the receiver size without the direct need of changing measurement procedures but with much higher significance as quality parameter for a key element of CSP technology.

Minimum specification of RP3 mirror panels should fulfill *FDx* of below 12 mm. Current state of the art for the standard focus deviation in mirror production is below 10 mm, and relevant potential is 8 mm or even below, with relevant impact on the solar field performance. A surface area of at least 98.5% of the mirror aperture area should be evaluated.

The verification of such specifications requires independent selection of mirror samples or continuous tracking of mirror production quality. Sufficiently powerful measurement systems beyond current manual measurements in the DLR Quarz Center facilities are required for stringent quality control.

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