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Analysis of parabolic trough concentrator mirror shape accuracy in different measurement setups

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Abstract

Mirror shape accuracy as a key optical performance parameter for parabolic trough collectors can be assessed accurately by common measurement systems proving the high quality of state-of-the-art mirror panels. However, measurement results cannot always be compared directly because critical boundary conditions are not yet standardized. This paper quantifies the differences in shape accuracy results between the most common measurement setups for parabolic trough mirror panels and identifies measurement position, mounting mode and support frame employed for the measurement as relevant boundary conditions.

Deflectometric measurements of mirror panels of RP3 geometry were performed at DLR's QUARZ Center Cologne in vertical (mounting points vertically and curved direction horizontally aligned) and horizontal measurement position (mirrors facing upward with mounting points horizontally aligned), both with and without tightening the mirrors to a support frame with screws. Finite element models were applied to calculate gravity-induced deformation and resulting slope and focus deviation on three different types of support frame: an ideally rigid support frame, a laboratory support frame, and an ideal support frame with elastic brackets.

The measurement results demonstrate that the difference in position and mounting mode can lead to relevant deviations of the shape accuracy results higher than the uncertainty of the employed deflectometric measurement system. For RP3 inner mirror panels a difference of up to 0.7 mrad in root mean square slope deviation (*SDx*) and 3.3 mm in root mean square focus deviation (*FDx*) from vertical to horizontal position was measured. Mirror shape specifications may thus not be applicable in all positions. Concerning the mounting onto different types of modeled support frame (in horizontal position) a variation of 0.5 mrad (*SDx*) and 1.8 mm (*FDx*) was calculated for perfectly shaped RP3 inner mirrors mounted onto an ideally rigid support frame compared to the case when mounted to a support frame with elastic brackets.

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Keywords: parabolic trough; mirror; shape accuracy; quality control; optical measurement; deflectometry; finite element modeling

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1. Introduction

Shape accuracy of the mirror panels for parabolic trough collectors significantly impacts the efficiency of a solar power plant. Several optical measurement techniques have been elaborated in the past that are suitable for assessing shape accuracy of mirror panels in test laboratories [1-4] as well as in quality control in series production [5].

According to manufacturers' specifications and quality control reports by independent test laboratories state of the art reflector panels for parabolic trough concentrators already reach very good shape accuracy values. Even though it is evident that shape accuracy results depend on, for example, orientation during measurement, the influence of the measurement boundary conditions are not yet quantified and are hence not documented. Consequently, laboratory measurement results are currently poorly comparable.

This paper presents an extensive study on the factors influencing mirror shape accuracy in laboratory measurement setups. The deflectometric measurement technique is employed to assess mirror shape accuracy of the most common mirror geometry (RP3 parabolic trough mirror, dimensions are 1700 x 1641 x 4 mm and 1700 x 1501 x 4 mm for inner and outer mirror respectively) in different laboratory measurement positions and mounting modes. Finite element models are utilized to quantify the influences of type and rigidity of the support structure onto which the mirrors are mounted for the measurement of mirror shape accuracy.

2. Optical measurement of mirror shape accuracy

2.1. Deflectometric test bench and description of common laboratory measurement setups

A highly accurate, highly resolving and fast technique to measure mirror shape accuracy is the so called deflectometry or fringe reflection method. It analyses the reflection of regular patterns and their distortions in the mirror surface in order to calculate local mirror slope deviation values sd, i.e. the angles between actual and ideal surface normal. Since the curved (x) direction is the trough's concentrating direction, the root mean square (rms) slope deviation value in x-direction is particularly a measure for the overall shape accuracy quality of parabolic trough concentrator reflector panels. It is calculated based on the area-weighted local slope deviation values:

$$SDx = \sqrt{\sum_{k=1}^{n}\left(sdx_k^2 \cdot \frac{a_k}{A_{tot}}\right)} \qquad (1)$$

with the surface element area a projected into the aperture plane, the total mirror aperture area A_{tot} and local mirror slope deviation values sdx in curved (x) direction. Since the maximum allowable value of slope deviation depends particularly on the distance of the reflecting surface element to the focal line, the deviation of the reflected light beam from the focal line in millimeters has been introduced as a further parameter characterizing mirror shape accuracy [6]. Local focus deviation values fd are derived from local slope deviation values sd and the distance d of the according reflecting surface elements to the focal line, e.g. in x-direction:

$$fdx = (2 \cdot sdx) \cdot d \qquad (2)$$

where the local slope deviation has to be multiplied by 2 because of reflection. Similarly to the rms slope deviation, a rms focus deviation value is calculated:

$$FDx = \sqrt{\sum_{k=1}^{n}\left(fdx_k^2 \cdot \frac{a_k}{A_{tot}}\right)} \qquad (3)$$

A detailed description of the deflectometric measurement method is given in [7]. The standard uncertainty of the rms value of measured slope deviation is stated to be less than 0.2 mrad [3]. The mean combined standard uncertainties of local slope deviation for the deflectometric test bench at DLR's QUARZ Center Cologne was determined to be $\bar{u}(sdx) \leq 0.7$ mrad [8].

Mirror shape accuracy of reflector panels for parabolic trough collectors is commonly measured in one of the following setups:

- vertical loose (vl): vertical measurement position without tightening of screws, mounting pads are vertically and curved (x) direction is horizontally aligned, mirror is carefully leaned against an ideally aligned support frame so that deformation due to dead load is negligible
- horizontal loose (hl): horizontal measurement position without tightening of screws, mounting pads are horizontally aligned, the mirror faces upward and is placed onto an ideally aligned support frame
- vertical fix (vf): mirror oriented as in vertical loose measurement setup, mirror mounting pads are fixed to the support frame with screws
- horizontal fix (hf): mirror oriented as in horizontal loose measurement setup, mirror mounting pads are fixed to the support frame with screws

2.2. Measurement of mirror shape accuracy in different laboratory positions and mounting modes

Deflectometric shape measurements of RP3 inner and outer mirror panels were performed in vertical loose, horizontal loose, vertical fix and horizontal fix measurement setup.

Mirror shape accuracy was measured for a total of eleven annealed sag-bent RP3 inner mirror panels of three different production periods, twelve annealed sag-bent RP3 outer mirror panels of three different production periods and five tempered press-bent RP3 outer mirror panels of one production period. For all setups the measurement data was evaluated in height (z-coordinate) and in slope and focus deviation in transversal (x) direction. In the presented study the whole mirror area was evaluated without neglecting a rim. Out of the spatially resolved data the root mean square values of local slope (*SDx*) and focus deviations (*FDx*) were calculated in x-direction. For the purpose of comparison, the root mean square values of slope and focus deviation were averaged for the different production periods. Only results of one production period were averaged because slope deviation characteristics slightly differ from one production period to another. Within one production period the standard deviation of root mean square slope deviation is acceptably low, i.e. smaller than twice the stated uncertainty of the measurement system of $u(SDx) = 0.2$ mrad.

3. Modeling of mirror shape accuracy

Finite element analyses were employed to examine the influence of the support structure on mirror shape accuracy. A total of three different finite element model cases for each mirror type were prepared in ANSYS Workbench for the study of the influence of type and rigidity of support structure on shape accuracy.

Reflector panels of RP3 geometry have dimensions of 1700 x 1641 mm and 1700 x 1501 mm for inner and outer mirror respectively. The mirrors are made of parabolically bent float glass sheets of 4 mm thickness. Four ceramic mounting pads are glued to the mirror rear side. Since the thickness of the reflector mirrors is small compared to their width and length they are modeled as shell bodies, having an ideal parabolic shape. The reflective and protective coatings are assumed to have no effect on the deformation behavior of the mirrors so that they are neglected in the models. The mounting pads are modeled as solid ceramic cylinders neglecting the borehole and the metal sleeve with internal thread that serves for fixation of the mirrors onto the support frame.

The performed static structural finite element analyses consider linear elastic deformation under steady-state conditions. Real material properties are used, inhomogeneity in material and geometry are neglected. Small parts like screws, screw nuts and washers are not included in the models. Real joints are not modeled, all parts are fixed permanently. In all model cases the mirrors are discretized utilizing solid shell elements. Solid elements are used for the modeling of adhesive, pads, brackets and further parts of the support frame. The study of grid convergence resulted in a division of 200 elements in width and length of each mirror panel. The individual model cases differ in type of support structure included in the models. Two models were prepared for each model case, one for RP3 inner mirror geometry and one for RP3 outer mirror geometry.

3.1. Analysis of mirror shape accuracy on different support structures

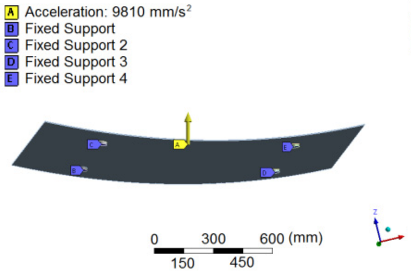
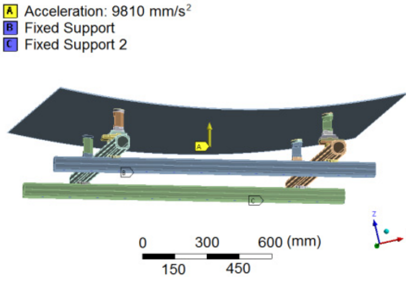
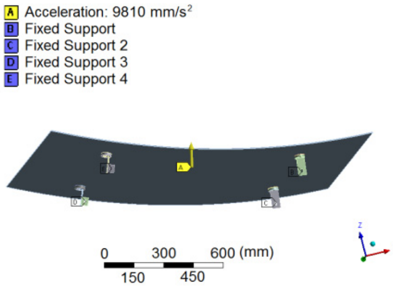
The finite element analyses were run in horizontal laboratory position for all model cases prepared for the examination of the influence of the support structure on mirror shape accuracy. In order to account for the mirror’s and structure's dead weight, standard Earth gravity was considered.

The utilized support structures are (compare Table 1): an ideal support structure (*ideal case*), a laboratory support frame (*fix laboratory case*), and an ideal support structure with EuroTrough brackets as linking elements to the mounting pads of the mirror panels (*elastic case*).

In the *ideal case* the mirror is fixed to an ideally rigid support structure. Fixed boundary conditions are applied to the rear side of the mounting pads. The fixed boundary condition constrains all degrees of freedom on the mounting pads' rear sides. There is neither displacement nor rotation possible at those locations. By definition, the mirror coordinate system's x-direction corresponds to the curved direction of the mirrors. The y coordinate axis runs parallel to the non-curved mirror edge. The point of origin is located in the parabola vertex corresponding to the back surface of the mirror panels. Z points from the vertex towards the focal line, corresponding to the optical axis. The mirror coordinate system's axes directions run parallel to the global ANSYS coordinate system's axes.

In the *fix laboratory case* the mirror is fixed with screws to the support frame used for the deflectometric shape measurements. Fixed boundary conditions are applied to the rear side of the bottom aluminum beams. The fix laboratory model case was validated using measurement data. Details of the validation procedure are described in [8].

Table 1: ANSYS models of one RP3 inner mirror panel in horizontal laboratory measurement position

ideal case	fix laboratory case	elastic case
		

In the *elastic case* the mirror is fixed by the brackets utilized in EuroTrough collectors to an ideally rigid collector structure. Fixed boundary conditions are applied to the side of the brackets which is attached to the collector structure.

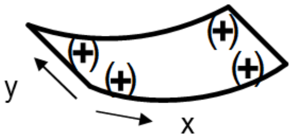
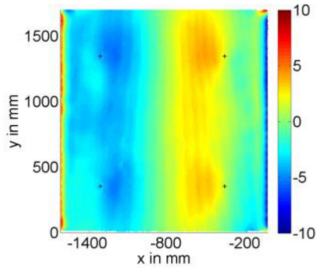
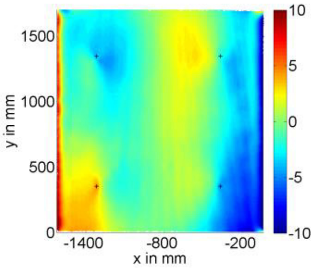
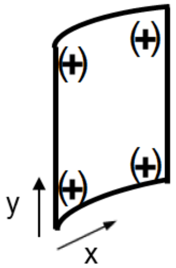
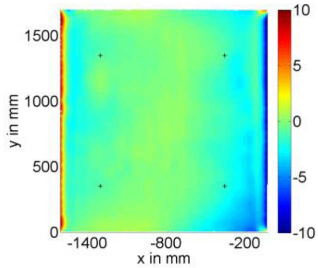
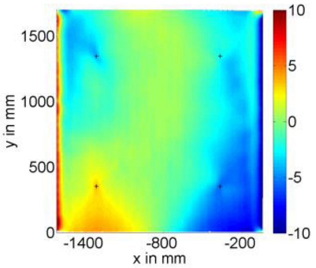
The finite element analyses yielded displacement data that was further processed to calculate local and rms slope and focus deviation values in transversal (x) direction. In a subsequent analysis the differences in local and rms slope and focus deviation values in transversal (x) direction between each two of these support structures were evaluated.

4. Results

4.1. Measured mirror shape accuracy in different laboratory positions and mounting modes

Table 2 depicts spatially resolved measurement results of a RP3 inner mirror panel in all four measurement setups.

Table 2: Slope deviation in mrad in x-direction for an exemplary annealed sag-bent *RP3 inner* mirror panel in vertical loose (vl) and horizontal loose (hl) laboratory measurement position (top) and vertical fix (vf) and horizontal fix (hf) laboratory measurement position (bottom)

	loose mounting mode	fix mounting mode
 horizontal loose (fix)	 $SDx_{\mathrm{hl,meas}}$ = 2.8 mrad	 $SDx_{\mathrm{hf,meas}}$ = 3.1 mrad
 vertical loose (fix)	 $SDx_{\mathrm{vl,meas}}$ = 2.0 mrad	 $SDx_{\mathrm{vf,meas}}$ = 3.0 mrad

Mirror panels sag inward between the mounting points from vertical to horizontal position. This is indicated by a change in slope deviation towards positive values in the inner mirror part between the mounting points and a change in slope deviation towards negative values in the outer mirror part between the mounting points. The inner mirror edge corresponds to the right side in the slope deviation graphics (small negative x-values). The outer mirror edge is located on the left side in the slope deviation graphics (high negative x-values).

Table 3 lists the root mean square values of slope and focus deviation in transversal (x) direction for inner and outer mirror panels averaged over each production period respectively.

The panels of production period A, B and C measured for this study perform best in vertical position and show an average increase of up to 0.7 mrad in *SDx* (RP3 inner, A) and up to 3.3 mm in *FDx* (RP3 inner, A) from vertical loose to horizontal loose position. The increase in root mean square values is less pronounced for outer mirror panels and if horizontal and vertical measurement position for mirrors fixed to the laboratory support frame are compared. An extraordinarily high increase in root mean square values can be noticed if results of fixed and loose measurements are compared for the outer mirrors C. Angular deviation of the mounting pads causes high local slope deviation values not only in the area around the mounting pads but affects shape accuracy of the whole mirror.

The examined tempered press-bent RP3 outer mirror panels (D) have got best shape accuracy parameters in horizontal position because spatial slope deviation characteristic counteracts gravity sag.

Table 3: Averaged root mean square slope (*SDx*) and focus deviation values (*FDx*) in x-direction for *RP3 inner* and *RP3 outer* panels in horizontal loose (hl), vertical loose (vl), horizontal fix (hf) and vertical fix (vf) laboratory measurement position

	RP3 inner				RP3 outer			
	SDx in mrad		*FDx* in mrad		*SDx* in mrad		*FDx* in mrad	
	vl, meas	hl, meas	vl, meas	hl, meas	vl, meas	hl, meas	vl, meas	hl, meas
A	2.1	2.8	7.4	10.7	1.4	1.5	6.9	7.5
B	2.1	2.7	7.6	10.2	1.4	1.5	6.8	7.8
C	2.3	2.9	8.6	11.0	1.5	1.7	7.4	8.4
D	-	-	-	-	2.0	1.5	9.6	7.3
	vf, meas	hf, meas	vf, meas	hf, meas	vf, meas	hf, meas	vf, meas	hf, meas
A	2.7	2.8	9.8	10.3	1.2	1.6	5.9	8.3
B	3.0	3.1	10.6	10.9	1.3	1.7	6.2	8.7
C	3.3	3.3	11.6	11.8	4.8	5.0	22.5	23.2
D	-	-	-	-	1.6	1.5	7.9	7.6

4.2. Modeled mirror shape accuracy on different support structures

Table 4 displays RP3 inner and outer mirror deformation under gravity load and resulting spatially resolved slope deviation values. As clearly indicated in the deformation side view graphics the type of support structure determines the typical deformation characteristic. Compared to the non-deformed model which is sketched as black line in the figures the RP3 inner mirror shows a symmetrical "M"-shaped deformation in curved direction when mounted onto an ideal (ideal case) or a laboratory support frame (fix laboratory case). The RP3 outer mirrors show also a "M"-shaped deformation which is non-symmetric when mounted onto a rigid support structure with brackets employed in EuroTrough collectors (elastic case). The mounting pads at the inner mirror part are attached via elastic "Z"-shaped brackets allowing the inner mirror part to bend toward the center leading to smaller displacement values at the inner edge. The deformation of a RP3 inner mirror in the elastic case resembles a "V"-shape with the mirror outer edge even turning upwards. Due to the smaller dimension of the RP3 outer mirror panels in curved direction, the forces acting on the elastic "Z"-shaped brackets are not that high that an upward deflection of the mirror inner edge is caused.

In general it can be stated that the less rigid the support structure, the more the mirror deflects in the middle. The maximum displacement Δz_{max} of an RP3 inner mirror in the middle differs between 0.36 mm (ideal case) and 0.9 mm (elastic case). For a RP3 outer mirror the maxima are between 0.35 mm (ideal case) and 0.5 mm (elastic case).

The different deformation characteristics directly translate into spatial distribution of slope deviation values. In the same way as for displacement values the less rigid the support structure the higher are maximum slope deviation values. When mounted onto the explained support structures, the rms of slope deviation values differ between 1.0 mrad and 1.5 mrad for a RP3 inner mirror and 0.9 mrad and 1.0 mrad for a RP3 outer mirror. Concerning rms focus deviation values the variation is between 3.7 mm and 5.5 mm and between 4.5 mm and 5.0 mm for inner and outer mirror respectively. Due to the larger distance of the outer mirror to the focal line higher focus deviation values are reached. For all cases deformation is stronger pronounced for inner than for outer mirrors resulting in higher displacement and thus slope and focus deviation values.

Table 4: Gravity-induced deformation of a *RP3 inner* and a *RP3 outer* ideally shaped mirror panel on different support structures and resulting slope deviation in x-direction in mrad. Scaling factor of deformation graphics: 1000

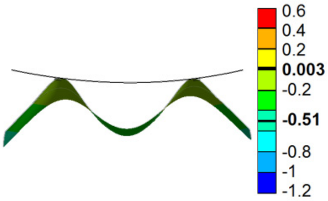
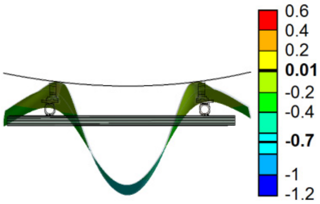
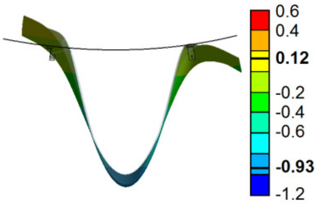
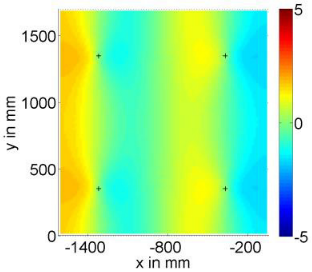
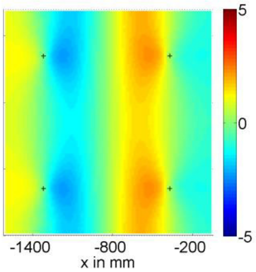
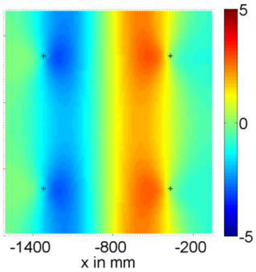
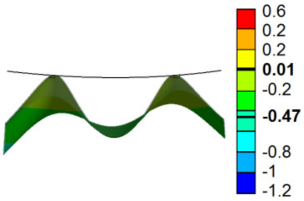
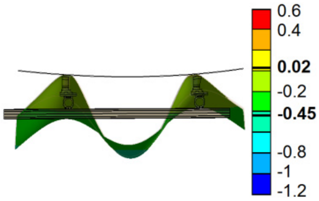
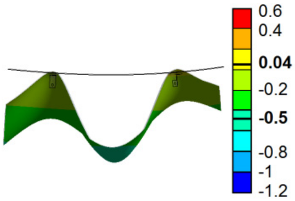
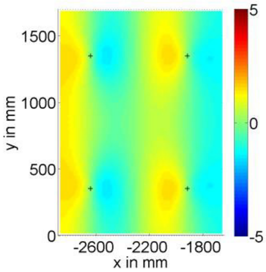
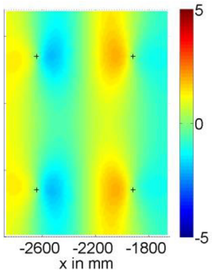
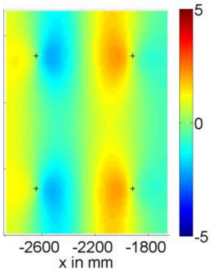
		ideal case	fix laboratory case	elastic case
RP3 inner mirror	deformation	 Δz_{max} = -0.5 mm Δz_{mid} = -0.36 mm	 Δz_{max} = -0.7 mm	 Δz_{max} = -0.9 mm
	slope deviation	 *SDx* = 1.0 mrad *FDx* = 3.7 mm	 *SDx* = 1.2 mrad *FDx* = 4.3 mm	 *SDx* = 1.5 mrad *FDx* = 5.5 mm
RP3 outer mirror	deformation	 Δz_{max} = -0.47 mm Δz_{mid} = -0.35 mm	 Δz_{max} = -0.45 mm	 Δz_{max} = -0.5 mm
	slope deviation	 *SDx* = 0.9 mrad *FDx* = 4.5 mm	 *SDx* = 1.0 mrad *FDx* = 4.7 mm	 *SDx* = 1.0 mrad *FDx* = 5.0 mm

Table 5 and Table 6 depict the differences in local slope deviation between each two of the examined support structures. As stated above, the rms slope deviation values of a RP3 inner and outer mirror increase by 0.5 mrad and 0.1 mrad respectively if elastic and ideal case are compared. In terms of root mean square of local slope deviation differences ($SDx_{lab-ideal}$, etc.), the results differ up to 1.3 mrad and 0. 5 mrad from one another for RP3 inner and outer mirrors respectively.

If local slope deviation values of the fix laboratory case and the elastic case are compared, the highest differences occur in the mirror areas where the elastically deformable "Z"-shaped brackets are located, i.e. in the outer area of the inner mirror and in the inner area of the outer mirror with respect to the parabola.

Table 5: Differences between gravity-induced slope deviation of a *RP3 inner* ideally shaped mirror panel mounted onto different support structures in x-direction in mrad.

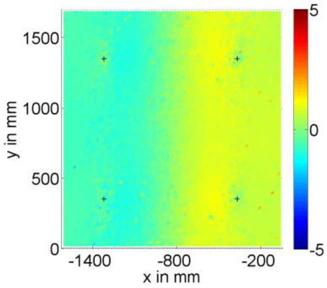
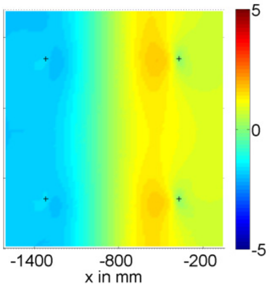
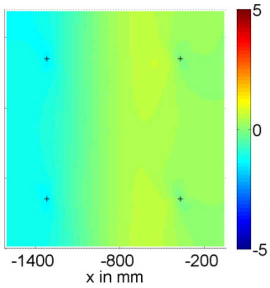
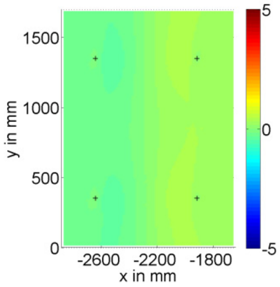
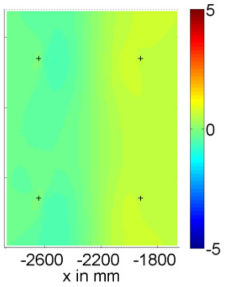
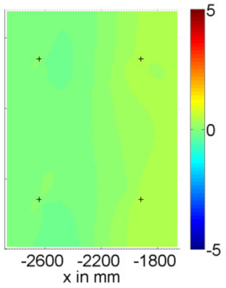
ideal – fix laboratory case	ideal – elastic case	fix laboratory – elastic case
		
$SDx_{\text{lab-ideal}}$ = 0. 7 mrad	$SDx_{\text{elastic-ideal}}$ = 1.3 mrad	$SDx_{\text{elastic-lab}}$ = 0.7 mrad

Table 6: Differences between gravity-induced slope deviation of a *RP3 outer* ideally shaped mirror panel mounted onto different support structures in x-direction in mrad.

ideal – fix laboratory case	ideal – elastic case	fix laboratory – elastic case
		
$SDx_{\text{lab-ideal}}$ = 0. 3 mrad	$SDx_{\text{elastic-ideal}}$ = 0.5 mrad	$SDx_{\text{elastic-lab}}$ = 0.2 mrad

5. Discussion

5.1. Mirror shape accuracy in different laboratory positions and mounting modes

As shown by deflectometric measurements in different laboratory setups the change of measurement position and mounting mode can lead to a significant change in shape accuracy parameter results that is higher than the stated uncertainty of the measurement system of $u(SDx)$ = 0.2 mrad. RP3 inner mirrors measured for this study show an average increase of up to 0.7 mrad in *SDx* and up to 3.3 mm in *FDx* from vertical loose to horizontal loose position.

The increase in root mean square values is less pronounced for outer mirror panels and if horizontal and vertical measurement position for mirrors fixed to the laboratory support frame are compared.

Mirrors that fulfill shape accuracy specifications in vertical position do not necessarily fulfill them in horizontal position (and vice versa), i.e. the annealed sag-bent inner mirrors examined in this study show FDx values of around 10 mm in horizontal loose position. This is higher than the specified focus deviation of 7 mm stated by mirror manufacturers for RP3 mirror panels. In vertical loose position the mirrors would meet the specifications if a rim of 5 mm is neglected which is common in industrial quality control measurements.

As indicated by the measurement results of the mirrors of production period C, the change in shape accuracy parameters from loose to fix mounting mode may even supersede commonly reached shape accuracy parameters if angular deviation of mounting pads is very high. The impact of angular mounting pad deviation on shape accuracy parameters is analyzed in detail in [8].

The difference in shape accuracy parameters from one measurement position to another depends on the specific spatial slope deviation characteristic. Dead load deformation can compensate or increase slope deviation in some areas of the measured mirror. Hence, for two mirrors of different slope deviation characteristic a different change in root mean square of slope and focus deviation will result.

5.2. Mirror shape accuracy on different support structures

The impact of type and rigidity of support structure on gravity-induced mirror deformation and resulting shape accuracy parameters were exemplarily examined for RP3 inner and outer mirror panels in horizontal laboratory measurement position employing finite element analyses and post-processing calculations.

Type and rigidity of support structure determine magnitude and characteristic of deformation and hence spatial distribution of shape, slope and focus deviation. Due to the smaller dimensions of the RP3 outer mirror panel the differences in shape, slope and focus deviation are less pronounced than for RP3 inner mirrors.

For comparison of results obtained in laboratory measurements the employed support structure needs to be documented. The difference in rms slope deviation values for RP3 inner mirrors mounted onto the different examined support frames is as high as or, in case of a rigid support structure with brackets employed in EuroTrough collectors (elastic case), even larger than the standard uncertainty of the root mean square value of $u(SDx) = 0.2$ mrad for deflectometric measurements. The rms slope deviation values of a RP3 inner and outer mirror increase by 0.5 mrad and 0.1 mrad, respectively, if the elastic case is compared to the case when mirrors are mounted onto an ideally rigid support structure (ideal case). The difference in local slope deviation values between each two of the examined support structures is larger than the mean combined standard uncertainties of local slope deviation of $\bar{u}(sdx) \leq 0.7$ mrad for RP3 inner mirrors but smaller for RP3 outer mirrors.

The determined gravity-induced deformation and resulting slope and focus deviations of an ideally shaped mirror on different support structures correspond to the deformation that would face a mirror measured in vertical laboratory position. In order to obtain shape accuracy results applying for a mirror evaluated in horizontal position on one of the support structures examined in this section, the determined differences in displacements, slope or focus deviations from one support structure to another would have to be added to the vertical results.

The differences in deformation and resulting shape accuracy parameters between each two support structures serve for comparison of mirrors measured on different support structures. The determined difference matrices would have to be added to results obtained on one support structure to obtain results applying to mirrors evaluated on one of the other support structures.

6. Conclusion

Shape accuracy of RP3 mirror panels in common laboratory measurement setups and mounted onto different support frames is examined using deflectometric measurements and finite element analyses.

The comparison of measurement results obtained in different positions and mounting modes shows a relevant change in local slope deviation values and thus also in rms of slope and focus deviation. Mirrors that fulfill shape accuracy specifications in one setup do not necessarily fulfill them in the other setups. Due to the smaller distance of the mounting points, the effects are in general smaller for outer mirrors than for inner mirrors and for mirrors fixed to the support frame with screws. However, if the mounting pads have high angular deviations a significant increase in shape accuracy parameters can be measured from loose to fixed mounting mode. The rigidity of the support frame to which the mirrors are attached has got a significant impact on deformation characteristic and thus on slope and focus deviation values. The effect increases for less rigid support frames.

The determined deviation of results in different setups implies that measurement position, mounting mode and support frame need to be documented in a complete statement of shape accuracy results. If measured mirror shape accuracy values are to be compared, standardized specifications concerning these boundary conditions are required.

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