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ScienceDirect

Solar Energy 111 (2015) 396–406

SOLAR ENERGY

www.elsevier.com/locate/solener

Conversion of parabolic trough mirror shape results measured in different laboratory setups

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Received 16 June 2014; received in revised form 12 September 2014; accepted 14 September 2014
Available online 19 October 2014

Communicated by: Associate Editor L. Vant-Hull

Abstract

Shape accuracy of mirror panels for parabolic trough solar collectors has a significant impact on the optical performance of the collectors in a solar power plant and is therefore carefully assessed by test laboratories and manufacturers. Relevant deformation is induced by gravity or mounting forces, so that shape accuracy data measured in different setups cannot be compared.

This paper presents a method for conversion of shape measured in a vertical laboratory setup into data for a horizontal laboratory setup. Characteristic deformation matrices for parabolic trough mirror panels of RP3 geometry are determined by deflectometric shape measurements on various mirror panels and by validated finite element analyses (FEA).

The resulting root mean square (rms) of measured slope deviation difference (i.e. the gravity induced deformation) between vertical and horizontal setup is on average 2.4 mrad for inner mirrors and 1.25 mrad for outer mirrors loosely positioned on a frame.

Measured data from vertical setup, transformed by such characteristic deformation matrices into horizontal shape results, differ by less than 0.2 mrad in rms slope deviation value from data measured in horizontal setup. Whereas the presented approach to convert shape accuracy measurement results is suitable for the calculation of rms values, some of the analyzed mirror samples show differences in local slope deviation values larger than the deflectometric measurement uncertainty. The amount of deviation depends on details of the accuracy of the positioning of the mirrors on the measurement frame and is affected by the fixation and associated mounting forces at the pads.

Keywords: Parabolic trough; Mirror shape; Deflectometry; Finite element analysis

1. Introduction

Shape accuracy of the mirror panels for parabolic trough collectors is a key parameter for optical performance that directly impacts the efficiency of a solar power plant. The high quality of state of the art mirror panels is ensured by measurements performed by independent test laboratories as well as by quality control in series production (Ulmer et al., 2012). Examples of common measurement techniques include the Video Scanning Hartmann Optical Test (VSHOT) developed by Sandia and NREL (Jones et al., 1997), visual inspection systems by ENEA (Montecchi and Maccari, 2007; Montecchi et al., 2011), and fringe reflection or deflectometry techniques by ISE (Burke et al., 2013), Sandia (Andraka et al., 2013) and DLR (März et al., 2011; Ulmer et al., 2011).

Measurement boundary conditions are not yet standardized and the shape measurements are performed in different setups that, for example, differ in measurement position. Previous work (Meiser, 2014; Meiser et al., 2014) quantifies the differences in shape accuracy results

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http://dx.doi.org/10.1016/j.solener.2014.09.021
0038-092X/

Nomenclature

a_{ij}	surface element area projected into the collector aperture plane (m^2)
A_{tot}	total collector aperture area orthogonal to the optical axis (m^2)
$\vec{n}$	ideal surface normal vector
$\vec{n}_+, \vec{n}_-$	actual surface normal vectors
sdx_{ij}	local slope deviation (mrad)
SDx	root mean square slope deviation in transversal (x) direction (mrad)
SDy	root mean square slope deviation in longitudinal (y) direction (mrad)
u	combined standard uncertainty of slope deviation (mrad)
$\bar{u}$	mean combined standard uncertainty of slope deviation (mrad)
x, y, z	coordinate axes

Subscripts

calc	calculated
comp	computed (by means of finite element analysis)
h, v	horizontal, vertical
f, l	fix, loose
meas	measured (by deflectometry)
n	upper bound of summation
rms	root mean square

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. If these boundary conditions deviate from one setup to the other, shape accuracy results cannot be compared. Moreover, shape quality specifications cannot be guaranteed to be met in different measurement conditions.

This paper presents a method to convert results obtained in different laboratory setups that allows the comparison of shape accuracy results. The examined setups are a vertical (mounting points vertically and curved direction horizontally aligned) and a horizontal measurement position (mirrors facing upward with mounting points horizontally aligned). Two cases are evaluated in both setups: the mirror tightened with screws to a support frame (fix case) and the mirror not tightened (loose case). The analyses are carried out for mirrors of RP3 geometry (focal length 1.71 m, trough aperture width 5.78 m, panel length 1.7 m) which is the most commonly employed mirror type in current parabolic trough power plant projects. Characteristic gravity-induced deformation and resulting slope deviation difference matrices are determined from measurement results obtained at the deflectometry test bench at DLR's Test and Qualification Center (QUARZ® Center) in Cologne and finite element analyses. They are added to vertically measured data to calculate horizontal results. The calculated results are compared to measured results in order to evaluate the accuracy of the suggested method. The finite element models prepared for this study are additionally validated.

2. Methodology

2.1. General definitions and description of reflector panels of RP3 geometry

In collectors that employ reflector mirrors of RP3 geometry the parabolic shape is formed by two inner and two outer mirror panels having dimensions of 1641 × 1700 mm (RP3 inner mirror) and 1501 × 1700 mm (RP3 outer mirror). They are made of 4 mm thick bent float glass sheets. Four ceramic mounting pads are glued to the mirror rear side for mounting it onto the collector support structure.

By definition, the point of origin of the according coordinate system is located in the parabola vertex (compare Fig. 1). The z-axis points from the vertex of the parabola towards the focal line. The y-axis runs parallel to the symmetry axis of the parabola and the x-axis points in the direction of mirror curvature.

Slope deviation is a measure for the shape accuracy of a mirror panel. Slope deviation values are typically measured spatially resolved and are defined as the angle between actual surface normal ($\vec{n}_+$ or $\vec{n}_-$, compare Fig. 1, right) and ideal surface normal $\vec{n}$. An outward rotation of the deformed surface normal vector relative to the original surface normal vector is defined as positive slope deviation value, an inward rotation as a negative value. By definition, the outward direction points to the outer edges of the parabolic trough, the inward direction toward the center of the trough.

Since gravity-induced deformation in non-curved (y) direction is less pronounced (Meiser, 2014) and the impact of slope deviation in y-direction on the intercept factor is of factor 10 lower than in curved (x) direction (Lüpfert and Ulmer, 2009), this study focuses on the evaluation of slope deviation values in x-direction.

2.2. Measurement of mirror shape accuracy and measured characteristic deformation

Deflectometry (also: fringe reflection) is an accurate and fast technique to measure shape accuracy of reflective surfaces with high resolution. A software algorithm uses the images of regular stripe patterns that are reflected and distorted by the surface to calculate local slope deviation values.

Reflector shape accuracy is furthermore evaluated in terms of standard deviation parameters of the reflector