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Determination of heliostat canting errors via deterministic optimization

Alberto Sánchez-González [a,*], Cyril Caliot [b], Alain Ferrière [b], Domingo Santana [a]

[a] Universidad Carlos III de Madrid, Department of Thermal and Fluid Engineering, Av. Universidad, 30, 28911 Leganés, Madrid, Spain
[b] Processes, Materials and Solar Energy Laboratory, PROMES-CNRS, 7 rue du Four Solaire, 66120 Font-Romeu-Odeillo-Via, France

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ABSTRACT

This paper presents a novel methodology to find out canting errors in the facets, i.e. mirror modules, of heliostats. An optimization procedure is established to fit simulated heliostat flux distributions to those captured on a white target. On the basis of a convolution-projection optical model, a deterministic algorithm – named DIRECT – has been successfully implemented, reaching correlation coefficients up to 95.8%. In this instance, the procedure has been applied to a THEMIS heliostat presenting canting errors of its faceted modules. From the optimization results, the heliostat modules were accordingly readjusted. And the heliostat optical quality has been significantly increased, validating the proposed methodology.

1. Introduction

Beam quality of heliostats depends on correct alignment. Heliostat alignment involves two operations: mirror focusing and heliostat canting. Mirror focusing consists in slightly bending the mirror surface into a concave shape, so that the size of the reflected sun image is minimized (Chong, 2014). Heliostat canting consists in tilting the mirror modules to aim at the same point. Proper heliostat alignment results in maximizing the annual power intercepted by the receiver (Jones, 1996b).

Heliostat canting techniques, on which the present study is focused, are classified into three categories (Ren et al., 2014): on-sun, mechanical, and optical alignment. In the first method, mirror modules are individually – and qualitatively – canted while the sun is impinging on the heliostat and the rest of the modules are covered. Mechanical alignment makes use of gauge blocks or inclinometers to adjust the orientation of the modules while the heliostat is in horizontal position; this method is very time consuming, just like on-sun alignment.

Six optical alignment techniques can be identified: laser method, camera look-back, photogrammetry, deflectometry, TOPHAT and H-FACET. There are two types of laser beam projection methods (Yellowhair and Ho, 2010): scanning prism laser projection and parallel laser beam projection. Camera look-back method was developed and successfully tested by SNL (Jones et al., 1994). Photogrammetry and deflectometry techniques utilize camera images to determine the orientation of heliostat facets. Theoretical overlay photographic heliostat alignment technique, TOPHAT (SNL, 2013), and heliostat focusing and canting enhancement technique, H-FACET (Sproul et al., 2011), are tools feed by camera images, both of which have been recently developed by SNL.

In this paper it is proposed a novel methodology to find out canting errors in focused heliostats to correct them. From heliostat experimental images taken in THEMIS solar power tower plant (research and development center operated by CNRS at Targasonne, France), an optimization procedure has been developed to minimize the difference between experimental flux distribution and simulations, where canting errors in the modules are the unknowns. The experimental set up and heliostat characteristics are described in the next section. Afterwards, the proposed procedure is described, and results for a heliostat with low optical quality are presented. From the results, the selected heliostat has been *in situ* readjusted to validate the proposed methodology.

2. Problem description

Misalignment of mirror facets leads to heliostats with poor optical quality. On a lambertian target near the receiver, flux distributions from misaligned heliostats result in images with multiple spots. To develop and validate a method to correct misaligned heliostat faceted modules, we use an heliostat from the THEMIS solar facility presenting canting errors. This section describes the characteristics of the heliostat and the experimental campaign carried out at THEMIS.

* Corresponding author.
E-mail addresses: asgonzal@ing.uc3m.es (A. Sánchez-González), cyril.caliot@promes.cnrs.fr (C. Caliot).

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Nomenclature

CCC	cross-correlation coefficient [–]
F	flux density [W/m^2]
f	focal distance [m]
FN	normalized flux density [–]
IL	intensity level [–]
N	number [#]
n	heliostat normal vector
RMSD	root mean square deviation [–]
s	sun vector
SD	standard deviation
t	target vector
TP	position of the target point
WC	position of the weighted centroid
X, *Y*, *Z*	Cartesian coordinate axes

Greek symbols

δ	angular canting deviation [mrad]
σ	Gaussian error [mrad]

Subscripts

elts	elements
exp	experimental
h	heliostat
m	module
max	maximum
mod	model
slp	slope
sun	sunshape

Acronyms

CCD	Charge-Coupled Device
CEST	Central European Summer Time
CNRS	Centre National de la Recherche Scientifique
CRS2	Controlled Random Search, version 2
DIRECT	DIviding RECTangles
H-FACET	Heliostat Focusing And Canting Enhancement Technique
MCRT	Monte Carlo Ray Tracing
PROMES	PROcédés, Matériaux et Énergie Solaire
SNL	Sandia National Laboratories
TOPCAT	Theoretical Overlay Photographic Heliostat Alignment Technique
UTC	Coordinated Universal Time

2.1. Canting errors in CETHEL heliostats

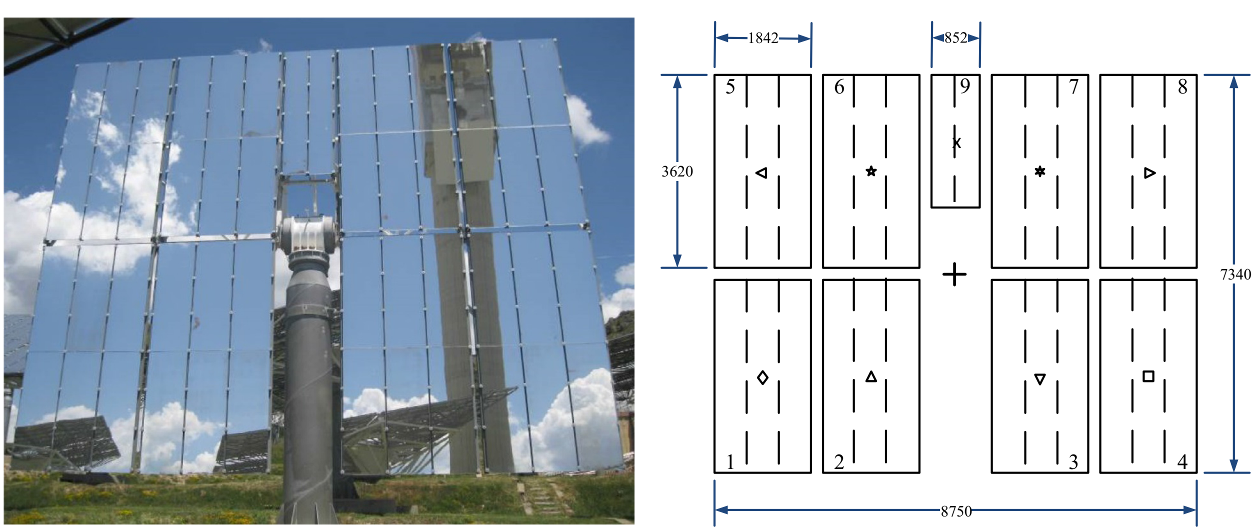
Heliostats in THEMIS field, whose model is named CETHEL, consist of 9 rectangular modules of mirrors. Eight modules are distributed in two wings at either side of the heliostat pole, and a ninth smaller module is in between and above the pole. Fig. 1 shows a photograph of one of the heliostats in the field (a) and a drawing with the dimensions of the heliostat and the modules (b). Total reflective surface is 54 m^2.

The module consists of three vertical strips of parabolic mirror; two strips in the complimentary module. Each mirror strip is mechanically tighten to the module frame so that curvature and orientation are forced. As a result, each module acts almost like a single spherical mirror with focal distance, f_m. This way, heliostat focusing is achieved. In this study, CETHEL heliostats are assumed to be properly focused.

Surface slope error (σ_{slp}), defined as the root mean square error of the true to the ideal spherical mirror shape, is not known. For CETHEL heliostats mirror slope error is expected to be around 1 mrad.

On the other hand, each module is supported on the rear heliostat structure in three points. Through adjustment of these three screw-nut assemblies, each module can be slightly tilted along its two axes; only one in the case of the complimentary module. This process is known as heliostat canting.

A heliostat is properly canted when the normal vectors of all the modules intersect in the same point. This point is the center of a sphere with radius $2 \cdot f_h$, being f_h the focal length of the heliostat. Fig. 2 represents the geometry of CETHEL heliostat with modules canted towards the same point. This is called on-axis alignment, because it is optimized for the case of heliostat center, target and sun falling in the same line; otherwise, the term off-axis alignment is utilized (Jones, 1996a).



(a) Front view photograph. (b) Geometry. Dimensions in mm.

Fig. 1. CETHEL heliostat.