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Absorber tube displacement in parabolic trough collectors – A review and presentation of an airborne measurement approach

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ABSTRACT

Parabolic trough collectors for concentrating solar sower plants are large scale optical devices with demanding requirements on optical and mechanical properties. Accurate mirror shape and absorber tube alignment are necessary to harness solar radiation with high efficiency. There are several methods to assess the shape of the mirror surface, yet there exist few approaches to effectively measure the position of the absorber tube. This paper provides a comprehensive overview on causes and effects of absorber tube displacement and on state of the art measurement techniques. A new approach on fully automated airborne absorber tube position measurement for parabolic trough collectors is presented, which outperforms existing methods concerning speed, spatial resolution, and level of automation, thereby achieving an accuracy of about 1.5 mm in vertical and lateral direction.

1. Introduction

The terms Concentrating Solar Power (CSP) or Solar Thermal Energy (STE) cover all methods where solar radiation is concentrated by lens- or mirror arrays before harnessing the thermal energy of the sun light. Among the different systems which are commercially available (Irena, 2013), the Parabolic Trough Collector (PTC) is considered the most mature technology with 4.2 Gigawatt (GW) installed capacity worldwide (CSP-Today, 2017). PTCs (Price et al., 2002; Fernandez-Garcia et al., 2010) are high precision optical devices, and the optical and mechanical properties of the concentrator and the Receiver tube (aka.: **H**eat **C**ollecting **E**lement) (HCE) are crucial for the efficiency of the power plant.

The optical performance depends to a large extend on the geometric accuracy of the concentrator. This share is commonly described by the Intercept Factor (γ), which is the ratio of irradiation hitting the absorber and reflected irradiation from the concentrator following the definition of Bendt et al. (1979, p. 9). Three independent geometrical properties determining the γ can be distinguished (Bendt et al., 1979; Pottler et al., 2014).

1. The shape accuracy of the mirror surface is commonly represented by slope deviations of the mirror from the design shape (Slope deviation in curvature direction (SD_X) and Slope deviation in longitudinal direction (SD_Y)). Mirror shape accuracy is considered to be the most important property for any CSP concentrator. It depends on the compliance with tolerances of the concentrator components (e.g. mirrors and structure), on the assembly accuracy and the concentrator's capabilities to withstand gravitational loads. A state of the art review on methods to determine the shape and/or slope deviations of CSP concentrators is presented in Ren (2014).
2. Tracking accuracy describes the deviation between the optical axis of the concentrator and the sun position, projected on the XZ plane of the concentrator (Bendt et al., 1979, Sec. 2.1, Fig. 2.1). Assuming a correct operation of the tracking system (mechanics, sun position algorithm, and optional sun-sensors), the local direction of the optical axis along the trough may be altered by wind, static unbalance and bearing friction. Such torsion effects are best assessed by means of inclinometers (Pottler et al., 2014).
3. This paper focuses on Absorber tube displacement along the optical axis (ΔZ_{Abs}) and Absorber tube displacement in lateral direction (ΔX_{Abs}). In all operation conditions, the absorber tube center line is supposed to be co-axial with the PTCs focal line.

There are several ways to estimate the impact of geometrical deviations on the γ. The statistical Ray Tracing (RT) approach presented in Bendt et al. (1979) consist of folding the sunshape with additional statistical concentrator errors, that way generating an

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Nomenclature

Abbreviations

CSP	Concentrating Solar Power
CSR	Circumsolar Ratio: (Buie and Monger, 2004)
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DNI	Direct Normal Irradiance [W/m^2]
DSG	Direct Steam Generation
EOR	Exterior Orientation: camera positions obtained by photogrammetric evaluation (Luhmann et al., 2006)
ET	EuroTrough Collector (Geyer et al., 2002)
FEP	Front End Plate: end face of Parabolic Trough Collector (PTC) steel structure orientated towards the drive pylon
GUI	**G**raphical **U**ser **I**nterface
GW	Gigawatt
HCE	Receiver tube (aka.: **H**eat **C**ollecting **E**lement)
HTF	Heat Transfer Fluid: see (Vignarooban et al., 2015)
IOR	Interior Orientation: Set of parameters describing the internal geometry and lens distortion of the camera (Luhmann et al., 2006)
KONTAS	Concentrator Test Bench at PSA, Almeria, Spain
LOS	Line-of-Sight
MATLAB	**MA**trix **LAB**oratory: proprietary programming language developed by MathWorks
NREL	National Renewable Energy Laboratory
PG	Close Range Photogrammetry
POI	Point of Interest
PSA	Plataforma Solar de Almería, Spain
PTC	Parabolic Trough Collector
PV	Photovoltaics
QFly	Airborne Qualification of CSP Plants
REP	Rear End Plate
REPA	**R**otation and **E**xpansion **P**erforming **A**ssembly: flexible tube connector or ball joint to link HCE with solar field header
ROI	Region of Interest
RP3	PTC Mirror quasi standard with 1710 mm focal length and 5774 mm aperture width
RT	Ray Tracing
SCA	Solar Collector Assembly
SCE	Solar Collector Element
SPRAY	**S**olar **P**ower **RAY**tracing Tool (Buck, 2010)
STE	Solar Thermal Energy (same as CSP)
STRAL	**S**olar **T**ower **RA**y tracing **L**aboratory (Belhomme et al., 2009)
TARMES	**T**rough **A**bsorber**R**eflection **ME**asurment **S**ystem
UAV	Unmanned Aerial Vehicle
WP	Waypoint of UAV flight route

Mathematical symbols and units

f	focal length
ΔX_{Abs}	absorber tube displacement in lateral direction
ΔZ_{Abs}	absorber tube displacement along the optical axis
γ	intercept factor: ratio of solar irradiation hitting the receiver versus irradiation reflected from the concentrator, when ρ_{Ref}, τ_{Glass}, and α_{Rec} were equal to 1 (Bendt et al., 1979)
SD_X	slope deviation in curvature direction
SD_Y	slope deviation in longitudinal direction
T_{HTF}	Heat Transfer Fluid (HTF) temperature
θ	PTC tracking angle: 90° corresponds to zenith
ρ_{Ref}	specular mirror reflectivity
τ_{Glass}	glass envelope tube transmissivity
α_{Rec}	absorber tube absorptivity

"effective" source with a wider angle distribution compared to the initial sunshape. Applications of statistical RT to PTC fields are presented among others in Lüpfert et al. (2007) and Pottler et al. (2014). A brief explanation on advantages and drawbacks of this method can be found in Zhu and Lewandowski (2012, Sec. 2.2.2).

An extensive analytical approach to determine the flux incident on an absorber tube considering statistical concentrator errors and a bent tube is presented in Khanna et al. (2013, 2014, 2015). An analytical approach called FirstOPTIC, which preserves the spatial information of shape- and absorber tube deviations while employing a probability approximation from Bendt et al. (1979) for the sun-shape was developed by Zhu and Lewandowski, 2012 and Binotti et al. (2012).

Numerical RT is the state of the art approach to assess the optical performance of CSP systems. Based on measured concentrator geometry, RT predicts the optical performance correctly even for cases where systematic deviations are present. RT simulations consider blocking and shading elements[1] which interfere with incident and reflected radiation. A current review on available RT tools and their abilities is available in Ho (2008) and Bode and Gauche (2012).

Absorber tube displacement may effect both the optical performance of the concentrator as well as the result of optical measurement techniques using the absorber tube position as an input parameter. This article was motivated by the development of Airborne Qualification of CSP Plants (QFly) (Prahl et al., 2011, 2013; Stanicki, 2011), where slope deviations of PTC solar fields are characterized by the **T**rough **A**bsorber**R**eflection **ME**asurment **S**ystem (TARMES) (Ulmer et al., 2009) approach, which in turn is based on the distant observer technique proposed by Wood (1981). For this approach, the absorber tube serves as a pattern. The absorber reflection visible in the mirror is used to deduce the mirror shape. Therefore it was necessary to develop a method suited to simultaneously measuring the absorber tube position along with mirror shape deviations. In addition, a reasonable statement on the optical performance by means of RT is only possible if the entire geometry is known with sufficient spatial resolution and accuracy.

Section 2 of this article describes the cause and effect of absorber tube displacement as well as applications of absorber position data. In Section 3, an overview on state-of-the-art methods to measure the absorber tube deviations is given. In Section 4, a new airborne approach for absorber tube positioning suited for large number of collectors is introduced and validated against a high-precision photogrammetric benchmark measurement. The results and further suggestions are discussed in Section 5.

2. Absorber tube displacement

The thermal energy absorbed by the HCE is transferred to a Heat Transfer Fluid (HTF) circulated inside the stainless steel tube with typical diameter in the range of 70–90 mm (Schott, 2015b,a). All HCEs designed for high temperature applications are surrounded by an evacuated glass envelope tube with an anti-reflective coating to minimize convection heat losses and to maximize the transmittance. A spectral selective coating of the steel tube assures high absorptivity an low radiative heat losses. The cost share of the HCEs is about 7% of the total investment cost of the entire plant

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[1] Bellow protections and receivers supports.