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A vector based freeform approach for reflecting concentrator of solar energy

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ABSTRACT

A vector based freeform approach is proposed for the geometrical reverse design of reflecting solar concentrators. The effect of solar cone angle of incident vectors is taken into consideration in the method based on three-dimensional freeform optics. The method developed is a closed-loop program and did not need any other commercial software. According to the transmission pattern of solar concentrators, the source-target mapping should be initially established prior to constructing an initial geometry formed by discrete points using the Geometric Construction Method. The freeform surface is generated by connecting several triangular flat elements defined by these points and then the Monte-Carlo ray tracing was conducted. The freeform surface can then be further optimized through feedback modifications. Finally, the optimal shape is obtained when the design examples are the off-axis freeform reflectors with target circular/rectangular receivers for the use of Concentrated Photovoltaic. This method provides a practical approach for improving the optical performance of solar concentrators.

1. Introduction

Concentrating photovoltaic (CPV) modules are capable of collecting sunlight onto solar cells by the use of optical concentrators thereby reducing the required cell area per unit of output power. Both optical efficiency and heat flux uniformity (Meng et al., 2013; Baig et al., 2014; Baig et al., 2016) are crucial evaluation factors for CPV. However, the traditional concentrators present uneven heat flux distribution, which leads to low-efficiency and short-lifetime of solar cells. Depending on the length and shape of light-pipe, a widely used flux homogenizer (Ries et al., 1997), the flux uniformity on solar cell can be improved. The optical efficiency, however, would be decreased to a different degree. The Köhler illuminator or integrator has been alternatively put forward (Hernándeza et al., 0000). An advanced Köhler integrator arrays based on Cassegranian-type design have been proposed to obtain high irradiance uniformity (Benitez et al., 2006). Besides, a symmetrical Cassegranian structure was designed to obtain high uniformity due to easy controlling of the ray vectors by orientating the secondary flat mirror (Meng et al., 2014).

The freeform optics has become another choice. The advancements of technology can contribute to the creation of more complex optical shapes. A freeform optical device helps to flexibly rearrange the normal vectors of local surface elements. This is mainly used in the field of illumination engineering (Fournier, 2011), to provide an efficient and desired target distribution. Theoretically, a target distribution can be obtained by using a freeform device as long as the incident vectors of solar rays are available (Fournier et al., 2010; Meng et al., 2016). At least one solution can be proposed, or even more.

The traditional solar concentrators such as the dish and Cassegranian-types, were usually applied based on point to point principle. The solar angular size was seldom considered. Instead, it was only discussed in the ray tracing simulations (Xia et al., 2012) because the solar cone angle is only 32′ and it was sometimes ignored. However, the resulted deviation would be enlarged for the concentrators with a long focal length or two-stage structures.

Considering the effect of solar cone angle, a new control method for the heat flux on a CPV module is proposed in this study. The method is a close-loop program that does not need any commercial software or file import/export operations. According to the transmission pattern of the solar concentrator, the source-target mapping would be initially established. After that the geometric construction method (GCM) is adopted for constructing an initial geometry formed by discrete points. The generated freeform surface (FFS) is next connected by a lot of triangular flat elements.

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Nomenclature

GCM	geometric construction method
FFS	freeform surface
MCRT	Monte-Carlo ray tracing
CPV	concentrated photovoltaic
(x, y, z)	Cartesian coordinate
(θ, r)	polar coordinates
I	solar irradiance from source, W/m^2
E	heat flux intensity at target, W/m^2
$\vec{P}$	points
V	vectors
i, j	subscript for discrete points/vectors along different directions
s	subscript for discrete points/vectors from the source
t	subscript for discrete points/vectors for target
R	pseudo-random number between 0 and 1
θ_s	solar cone angle
$\boldsymbol{M}_0$	vector of incident rays
$\boldsymbol{N}$	normal vectors
$\boldsymbol{T}$	next surface hit by the rays
$\boldsymbol{S}$	bound of light spot caused by solar cone angle
E_0	target heat flux
Ef_k	modified heat flux
E_k	simulated heat flux
β_k	Feedback coefficient
MF	merit function
C_E	concentration ratio

Then, the Monte-Carlo ray tracing (MCRT) can be conducted and would be further optimized by feedback modification method. Finally, an optimal shape would be obtained as well as the ideal FFS for target distribution. The current method provides a new approach for the geometrical reverse design of solar concentrators.

2. Mechanism of heat flux distribution by freeform solar concentrator

The uniformity of the heat flux on solar panel deeply influences the output efficiency. For a point optical source, the distribution may become perfectly uniform after optimizations. However, overlapped focal spots would inevitably form a Gaussian distribution, especially for the traditional dish type concentrators when the solar cone angle (with pillbox sunshape in this article) is considered.

For example, considering a circular receiver as a target, the uniform flux region around the center can be obtained through freeform optical design instead of the original Gaussian region. Based on the point to point mapping assumption, there would be infinite focal points hitting the target surface. As shown in Fig. 1, if the solar cone angle is considered, the emitting ray from each source point would form a limited area of the focal spot at target. The spots '1' and '2' located at the edge of a uniform and Gaussian region respectively could be in arbitrary shape. The dividing line can be generated via linking the internal tangent of spot '2' only if the inscribed spots such as '2' along the edge of the solar panel are found. Therefore, it is possible for the spots at the inner side of '1' to be fully overlapped with each other. Outside the spot '1', however, the area of every focal spots cannot be fully covered. As a result, the uncovered area would be enlarged as the spots move outwards, presenting a Gaussian distribution. In practical applications, the part of Gaussian region should be truncated to increase the uniformity of receiving heat flux.

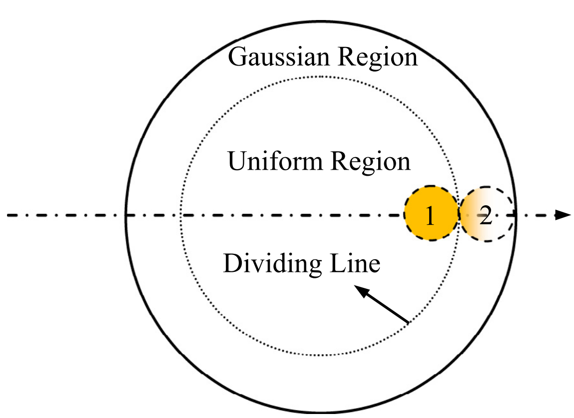

Fig. 1. Optimized heat flux distribution on the circular solar panel.

3. Distribution control method using freeform concentrator

Limited by current technology of mechanical processing, the large-scale solar concentrators are normally joined by several small facets, which are treated as the small elements of FFS in the current study. The normal vectors of these elements would be optimized to obtain a target flux distribution when the manufacturing and assembling process are held similar. In other words, a better target heat flux is possible with the same cost. For the small size of concentrator, the precise optical processing is needed and a surface with smooth geometrical structure become necessary. The current approach provides some references for the constructions of smooth FFS.

Owing to the variety of practical applications, there is no common method for the creation of FFS. Available methods include multi-parameter optimization (Benítez and Miñano, 2007), Wassermann-Wolf differential equation method (Cheng et al., 2010), tailoring method (Ries and Muschaweck, 2002), point-to-point mapping (Fournier et al., 2010), simultaneous multiple surface (SMS) Dross et al., 2004 and GCM (Fournier, 2011). The optical design methods for 2-D freeform systems with rotational or extruded symmetry have been thoroughly studied via SMS (Miñano et al., 2009) and GCM (Tsai, 2015). However, the 3-D system still faces challenges when the simple ray aiming approach does not work. The main obstacle lies in the solution of the Monge-Ampere elliptical nonlinear partial different equation (Winston et al., 2005). Several approaches have been proposed to tackle this problem (Ries and Muschaweck, 2002; Oliker, 2005; Caffarelli et al., 1997). GCM and source-target mapping have been applied for the creation of discontinuous freeform surface (Wang et al., 2007). This approach is an effective way that may avoid solving the Monge-Ampere partial different equation (Luo et al., 2010). A similar mapping method has been extended to the design of smooth 3-D surfaces based on the initial mapping approximate solution combined with feedback modifications (Mao et al., 2014).

The current study aims to obtain the target distribution mainly for CPV applications with the aid of freeform technologies. The model can also be extended to solar thermal or other fields. Some novel freeform CPV modules have already been developed, such as