Shape measurement and reconstruction of solar concentrator based on two-dimensional phase shift method

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\textbf{Abstract}

Deflectometry is used to measure the three-dimensional profile of the solar concentrator because of its high accuracy and short inspection time. In order to obtain the shape of concentrator, two different phases usually have to be computed for a single area. The two phases are calculated by using two sets of the phase-shifting patterns with two different directions, respectively. In this paper, a new two-dimensional phase shifting method is proposed to obtain two phases with different directions with a single set of 2D phase, which reduces the number of acquired images and increase measurement speed. On the other hand, it is necessary to acquire the shape, which must be calculated from the slopes of the measured object. Existing integration techniques have some drawbacks that render them unusable in many cases. An approximation employing radial basis functions is applied to reconstruct the shape of concentrator, and reconstructs surfaces both locally and globally with high accuracy. Finally, experiments in measuring the shape of RP3 mirror demonstrate the proposed method’s performance.

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\textbf{1. Introduction}

In a concentrating solar plant, the solar field consisting of a large number of collectors, which collects and concentrates the solar energy onto the receiver, is the major cost component of a plant. To obtain a homogeneous
flux distribution on the receiver, the collectors' shape must be highly precise to lower the energy losses. The ideal shape and optical efficiency of the collector maximizes the energy input of the receiver and has a high impact on the plant performance. Therefore, it is very important to test and evaluate the quality of the surfaces for guaranteeing the optical performance. However, due to technical restraints in the manufacturing and installing process, deviations from the optimum collector shape leading to energy losses on the receiver cannot be completely avoided. On the other hand, it is necessary to monitor and adjust the optical quality of the collectors in the manufacturing process. To test and qualify the collectors, a measurement tool for measuring the surface profile with adequate precision should be needed.

Many different techniques for shape measurement of solar collectors have been proposed by a variety of researchers in the past decades. In 1978, Sandia National Laboratories presented a measurement system based on a laser ray trace tester for parabolic trough solar collectors[1]. This system scans the surface with a laser beam, detects the reflected beam on a target and obtains the normal of the collector surface. The VSHOT system developed by Sandia measures the slopes of a parabolic dish. This system is sufficiently accurate, but the setup is time consuming and the implementation to large surfaces might be difficult. This limitation is overcome by photogrammetry which is used to measure 3D shapes by calculating the coordinates based on a series of photographs taken from different positions[2]. This method is also time consuming and not suitable for large surfaces since the measured surface has to be equipped with a large number of target points. Recently, Ulmer et al. developed a new method for measuring the slope error of heliostat based on deflectometry[3-6]. Later, we use the similar approach combined with temporal phase unwrapped technique and novel easy calibration method to measure the heliostat facet[7]. And there are some other methods to measure the shape of solar collector[8-16].

Traditionally, in order to obtain phase information of the measured object, two sets of one-dimension sinusoidal fringe patterns are usually used: horizontal and vertical. This increased number of images obstructs fast measurement of specular shape based on fringe reflection. In this paper, a two-dimension phase-shifting method is proposed to reduce number of images: the vertical and horizontal sinusoidal fringes are superposed to compose a two-dimension sinusoidal pattern, and it is shifted in 2D space to provide phase information in each direction. Therefore, only five fringe images are need for measurement.

Actually, one of the major challenges in fringe-reflection measurement is to realize the shape reconstruction effectively and efficiently. In several cases it is sufficient to know the local gradient; however, it is also important to obtain the height information of the solar collector as well. If the shape is known, it is easy to align the collector according to the measurement results. To obtain the shape of the solar collector, a numerical shape reconstruction method is needed. Essentially there are two different approaches for integration: local and global integration techniques[17,18]. Local method: it integrates along predetermined paths. The advantage of this method is that it is simple and fast. However, the locality of calculation causes a high dependency from data accuracy, and the propagation of height increments along paths also means propagation of errors. Global method: it tries to minimize a designed cost function. The advantage of this method is that there is no propagation of error. But the implementation has certain difficulties and somehow is not easily convergent.

This paper proposes the fringe reflection technique to measure the reflective surface of a solar collector using two-dimension phase-shifting method. Based on an approximation employing radial basis functions and a special iterative algorithm, the height information of the collector can be reconstructed, which has the properties of both local and global integration methods: it needs to preserve local details without propagating the error along a certain path, it also yields a globally optimal solution in a least squares sense. Finally, the presented method shows the ability to provide accurate measurement of the RP3 solar collector and a prototype of a measurement system has been developed.

2. Two-dimensional phase shift method

A general expression of the image of the two-dimension fringe pattern $I$ captured by the camera is

$$I(x, y) = a(x, y) + b(x, y)[\cos(\phi_x(x, y) + a_x) + \cos(\phi_y(x, y) + a_y)]$$  \hspace{1cm} (1)
where $\varphi_x$ and $\varphi_y$ denote $x$ and $y$ directional phase, $a_x$ and $a_y$ are the phase-shifting angles in each direction. The formula (1) can be rewritten as

$$I = A_1 + A_2 \cos a_x + A_3 \sin a_x + A_4 \cos a_y + A_5 \sin a_y$$

(2)

where $A_1 = a, A_2 = b\varphi_x, A_3 = -b\sin \varphi_x, A_4 = b\cos \varphi_y, A_5 = -b\sin \varphi_y$. Based on phase-shifting method, Eq.(2) can be expressed in matrix form as

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} 1 & \cos a_{x1} & \sin a_{x1} & \cos a_{y1} & \sin a_{y1} \\ 1 & \cos a_{x2} & \sin a_{x2} & \cos a_{y2} & \sin a_{y2} \\ \vdots & & & & \\ 1 & \cos a_{xN} & \sin a_{xN} & \cos a_{yN} & \sin a_{yN} \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_N \end{bmatrix}$$

(3)

The coefficients $A_1, A_2, A_3, A_4$ and $A_5$ can be solving Eq.(3) by using least square method:

$$A = A'K$$

(4)

where

$$A' = \begin{bmatrix} 1 & \cos a_{x1} & \sin a_{x1} & \cos a_{y1} & \sin a_{y1} \\ 1 & \cos a_{x2} & \sin a_{x2} & \cos a_{y2} & \sin a_{y2} \\ \vdots & & & & \\ 1 & \cos a_{xN} & \sin a_{xN} & \cos a_{yN} & \sin a_{yN} \end{bmatrix}, \quad K = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix}, \quad A = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_N \end{bmatrix}$$

From Eq.(2) and (4), the phase in $x$ and $y$ direction can be obtained:

$$\varphi_x = \tan^{-1}\left(-\frac{A_3}{A_2}\right), \quad \varphi_y = \tan^{-1}\left(-\frac{A_5}{A_4}\right)$$

(5)

Based on Eq.(4) and (5), five fringe images are enough to determine the phase $\varphi_x$ and $\varphi_y$. In this paper, the five-step phase-shifting case is used. The phases are given by

$$\varphi_x = \tan^{-1}\left(3\frac{I_2-I_4}{-2I_1+I_2+2I_3+I_4-2I_5}\right), \quad \varphi_y = \tan^{-1}\left(3\frac{I_1-I_5}{I_1-2I_2+2I_3-2I_4+I_5}\right)$$

3. Shape reconstruction

Based on fringe reflection method, it is easy to find out that not only the slopes but also the height of the collector surface has an influence on the position of the observed point on the screen. In order to obtain the height of object, we should reconstruct the collector shape from gradient data, which is very important to absolutely measure and evaluate the optical character of solar collector. To reconstruct the shape, one has to use the numerical integration method. But, most existing methods have different drawbacks: they either suffer from error propagation, or they
introduce global errors due to unknown boundary conditions. The desired shape reconstruction method should have both local and global integration methods, which means that it should preserve the local details without propagating the error along a certain path. In this paper, the interpolation approach is used to reconstruct the shape from gradient data. The gradient data is given as pairs \((p_x(X_i), p_y(X_i))\), where \(p_x(X_i)\) and \(p_y(X_i)\) are the measured slopes of the collector at \(X_i\) in \(x\) and \(y\) directions, respectively (\(1 \leq i \leq N\)). Define the interpolate to be

\[
z(X) = \sum_{i=1}^{N} \alpha_i \phi_x(X - X_i) + \sum_{i=1}^{N} \beta_i \phi_y(X - X_i)
\]

where \(\alpha_i\) and \(\beta_i\) are coefficients and \(\phi\) is a radial basis function. \(\phi_x\) and \(\phi_y\) denote the analytic derivative of \(\phi\) with respect to \(x\) and \(y\), respectively. To obtain the coefficients in Equation (2), the analytic derivatives of the interpolate \(\phi\) with the measured gradient data are matched as:

\[
\begin{align*}
    z_x(X_i) &= p_x(X_i); \quad z_y(X_i) = p_y(X_i); \\
    \phi_{xx}(X_j - X_i) \quad &\phi_{xy}(X_j - X_i) \quad \alpha_i = \begin{pmatrix} p_x(X_i) \\ p_y(X_i) \end{pmatrix} \\
    \phi_{xy}(X_j - X_i) \quad &\phi_{yy}(X_j - X_i) \quad \beta_i
\end{align*}
\]

The coefficients can be determined by solving the following linear equations:

\[
\begin{pmatrix} \phi_{xx}(X_j - X_i) & \phi_{xy}(X_j - X_i) \\ \phi_{xy}(X_j - X_i) & \phi_{yy}(X_j - X_i) \end{pmatrix} \begin{pmatrix} \alpha_i \\ \beta_i \end{pmatrix} = \begin{pmatrix} p_x(X_i) \\ p_y(X_i) \end{pmatrix}
\]

Based on the resulting coefficients \(\alpha_i\) and \(\beta_i\), the collector surface can be reconstructed by using the interpolate in Equation (6). The radial basis function \(\phi\) can be chosen to be the Wendland’s function:

\[
\phi(r) = \frac{1}{3} (1 - r)^6 (35r^2 + 18r + 3), r = \sqrt{x^2 + y^2}
\]

In the measurement, the amount of data is rather large. To solve such large data, the following method is presented: firstly, the data sets are split into a set of overlapping patches. On each patch, the data is interpolated and the calculated up to a constant of integration. Secondly, the least-squares fitting scheme is used to obtain the reconstructed surface on the entire field.

4. Experiment result

An experimental investigation of the feasibility of the proposed method is carried out as well. A RP3 inner mirror is measured with the fringe reflection technique. Figure 1 shows the measurement setup. Five-step 2D phase-shifting fringe patterns are projected on the target screen, the distorted patterns are captured by CCD camera. Figure 2 (a) - (b) show the unwrapped phase distribution in both \(x\) and \(y\) directions, respectively. The virtual reference phase distribution is given in Figure 3. The slope data and slope error data are shown in Figure 4. The proposed reconstructed method is then utilized to integrate the gradient data to reconstruct the shape of collector, which is shown in Figure 5. The slope errors (RMS) are: 1.6129mrad (\(x\)-direction), 0.1082mrad (\(y\)-direction). The reconstructed shape error of RP3 inner mirror is 0.01235mm. And the focal length measured is 1709.66mm.
Fig. 2. (a) Unwrapped phase distribution in x-direction; (b) Unwrapped phase distribution in y-direction.

Fig. 3. (a) Reference phase distribution in the x-direction; (b) Reference phase distribution in the y-direction;
Fig. 4. (a) Slope distribution in the x-direction; (b) Slope distribution in the y-direction; (c) Slope error distribution in the x-direction; (d) Slope error distribution in the y-direction;

Fig. 5. (a) Reconstructed shape of RP3 inner mirror surface; (b) Reconstructed error.

5. Conclusion

In this paper, a solar collector surface measuring system based on 2D phase-shifting fringe reflection technique is built, and the measurement system setup is very easy. Several fringe patterns are projected onto a target screen and the deformed patterns modulated by the measured collector are captured by CCD camera. A shape reconstruction method based on approximation employing radial basis functions is proposed. The experiment measurement results demonstrate that not only are fine details preserved, but also the global shape is reconstructed as well, and even higher global accuracy. Furthermore, this measurement system makes it possible to measure a large class of solar collectors.

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