Geometric measurement of film-cooling holes using co-axial light-field imaging

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ABSTRACT
In a high thrust-weight-ratio aero-engine, turbine blades are exposed to extremely high temperature and pressure which sets higher demands in the blade cooling technology. The mainstream types of cooling include internal airflow cooling, film cooling, and thermal barrier coating. Cooling efficiency is substantially subject to the machining accuracy of blades, more specifically the film-cooling holes on them. A coordinate measuring machine (CMM) is extensively used in the measurement and inspection of turbine blades which enables measuring blade patterns and building geometric models. However, the probes utilized by a CMM are similar in scale to that of a film-cooling hole, making it almost impossible for a CMM to measure film-cooling holes. The probes are prone to damage and the measurement accuracy cannot be guaranteed. This paper proposed a non-contact measuring technique to cope with the inspection of turbine blades. The technique is based on light-field imaging. A light-field camera with a high magnification lens is applied to capture images of film-cooling holes and their neighborhood which are then input to a 3D reconstruction algorithm. A point cloud is derived by the algorithm and fundamental parameters are extracted. The whole inspection requires only one platform and is able to measure shaped film-cooling holes.

INTRODUCTION
With the rising demand for a longer life-span and higher performance of aero-engines, more sophisticated film-cooling holes (FCHs) are being employed in hot end components such as combustor and turbine to ensure the safe running and the long life of the engine. Cooling techniques for high-pressure turbine blade is a combination of internal cooling and film cooling (Sunden and Xie 2010). Various advanced cooling techniques have made it possible to expose turbine blades to a higher gas temperature. Many studies have found that the design of FCHs, especially by using shaped holes, will help boost cooling efficiency significantly (Bunker 2005, Silieti, Kassab et al. 2005, Bunker 2009, Liu, Malak et al. 2010). The widely used FCHs nowadays are round and fan-shaped ones subject to structural strength and limitations in the machining process. Non-traditional machining process, namely laser drilling (Schulz, Eppelt et al. 2013), electrodischarge machining (EDM), and electrochemical machining (ECM) (Weingärtner, Kuster et al. 2012, Rajurkar, Sundaram et al. 2013), are facing challenges in guaranteeing consistency and reliability of FCHs. The main procedures of the commonly used EDM are drilling, coating, and expanding. These operations will have an impact on the stability of machining quality. Comparatively, laser drilling, particularly femtosecond laser, can improve the quality of FCHs effectively but is susceptible to machining environment and laser parameter. Moreover, the polarization of light tends to deform the shaped holes (Weber, Michalowski et al. 2011). Other studies (Gritsch, Schulz et al. 2001, Gritsch, Colban et al. 2005) have suggested that machining errors of FCHs will lead to local blockage during operation and thus cause changes in the geometric parameters (cross-sectional area, equivalent diameter, exit angle) upon which cooling efficiency is dependent.
A highly efficient and high-precision inspection technique for massive FCHs on hot end components in an aero-engine is urgently demanded to ensure machining quality and to prolong life-span of the components. There are a few proven techniques that address inspection and at least meet the industrial requirement.

These techniques include a coordinate measuring machine (CMM) that applies a probe in detecting the profile of a blade. The probe is moved according to a planned path along the blade surface. The size of the spheric probe is taken into consideration by an algorithm to resolve 3D coordinates of the sampled points. CMM can barely be employed in a measurement task of FCHs as the diameter of probes with even the smallest size is still larger than that of the hole exit section. Some researchers have investigated the usage of micro-probes whose diameter is around 50µm. They use fiber deflection probes to reconstruct the inner morphology and depth of FCHs (Gritsch, Colban et al. 2005, Muralikrishnan, Stone et al. 2006) Though being highly accurate, the point-by-point scanning approach falls behind in terms of efficiency.

Measurement based on 2D imaging is a non-contact one that is aimed at improving accuracy and efficiency. Imaging devices and a turbine blade are mounted on a high-precision translational and rotational platform for the acquisition of information. Image recognition algorithms are then applied to obtain hole diameter and shape. Though being convenient and fast in its implementation, this technique fails to detect depth information and thus is insufficient in obtaining comprehensive hole parameters.

The main focus of FCHs inspection is the measurement of diameter and exit angle of round FCHs whereas few methods have been dedicated for measuring section area, equivalent diameter, exit angle of shaped holes. This problem belongs in nature to 3D geometric measurement. Laser beam scanning (Shetty, Eppes et al. 2009, Bezdecny, Graham et al. 2015) and acoustic emission touch testing (Bezdecny, Graham et al. 2015, Elfurjani, Ko et al. 2016) are proposed for measuring 3D information of micro-holes, yet they are facing certain limitations and challenges when it comes to productization. Laser beams tend to reflect several times on the inner surface of micro-holes, resulting in difficulties in image capture. Acoustic ways are way less efficient than a production line requires. Methodology that addresses fast and robust FCHs inspection should be the research focus of the coming stage. This paper is based on previous researches of 3D reconstruction via light-field imaging (Ding, Li et al. 2019, Ma, Qian et al. 2019) and it describes the exploration of fast light-field imaging technique in the inspection of FCHs.

CONCEPT OF LIGHT-FIELD IMAGING

It is possible to describe light propagation by assigning a plenoptic function for each light ray. An arbitrary point on a light ray can be represented by a 5-dimensional plenoptic function, i.e. light-field function, \( L(x, y, z, \theta, \varphi) \) (Adelson and Bergen 1991, Adelson and Wang 1992). \((x, y, z)\) are spatial coordinates and \((\theta, \varphi)\) are azimuth and elevation angles as shown in Figure 1. In the case of measuring FCHs, light is considered to propagate in a uniform media without any blockage. The 5D representation can be thus simplified to a 4D one as \( L(u, v, s, t) \). As indicated by Figure 1(b), an object can be reconstructed by back-propagating a completely recorded 4D light-field.

![Figure 1(a) 5D and (b) 4D light-field representation of a light ray](image)

Unfortunately, to obtain clear images, the traditional 2D imaging technique uses image sensors to gather focused light rays that propagate from an object, go through the camera lens system, and reach some pixels on the sensor plane. This kind of imaging process records only intensity and spatial information of incident rays while missing the angular information of light rays. As suggested by Figure 2, the principle of light-field imaging is different from the traditional 2D imaging. A micro-lens array (MLA) is mounted in front of the image sensor in a light-field camera to split light rays. The split rays are then recorded by the image sensor as angular information. This kind of camera architecture allows 4D plenoptic functions to be recorded and enables 3D object reconstruction.

The whole imaging process demonstrated in Figure 2(b) can be described as light rays from an object, a representation of a FCH in this case, going through the camera main lens system and reaching the MLA plane. Each micro-lens will split rays with different orientations and project them onto different pixels on the image sensor, meaning there is a connection between one object point and a couple of pixels even if the camera is ideally focused on the object. The images recorded by a light-field camera are called raw light-field images here. According to the light-field imaging principle, each pixel beneath a micro-lens corresponds to a unique incident angle. The number of pixels one micro-lens covers is thus a measure...
of angular resolution of a recorded light-field (Ng, Levoy et al. 2005, Georgiev, Zheng et al. 2006). By rendering a raw light-field image, sub-aperture image array can be obtained which represents images resulted from different viewing angles. In this way, a light-field camera can be treated as a virtual array of small cameras. The 3D reconstructing algorithm is based on converting images with parallax into a point cloud of the recorded objects.

Figure 3 displays the flow chart of the FCHs inspection method based on light-field imaging. The centers of each micro-lens must be measured before any further operations can be performed. This step is called the MLA calibration. There are two feasible ways of MLA calibration. One way is to take an image of a whiteboard with diffuse reflection. The other way which is adopted in this paper is to adjust the camera aperture to its minimum and record the image of such a whiteboard. By locating micro-lens centers on the image, coordinates of each micro-lens are calculated. After MLA calibration, perspective shift is performed to extract sub-aperture images. A camera metric calibration is implemented before the 3D reconstruction takes place. These two procedures produce a point cloud of the measured area. Finally, feature extraction is carried out for extracting FCH parameters.

**Figure 2 A comparision between (a) traditional 2D imaging and (b) 4D light-field imaging**

**Figure 3 Flow chart of the methodology**

**PRINCIPLES OF THE MEASUREMENT TECHNIQUE**

**Extracting sub-aperture images**

After obtaining centers of each micro-lens, an area of N-by-N pixels is identified beneath each micro-lens. By taking out a specific pixel with the same local coordinates from each micro-lens and rearranging them, a sub-aperture image of a certain viewing angle is generated. From the perspective of light-field imaging, the intersection of a light ray with the camera main lens is regarded as \((u, v)\), then the intersection of the same ray with the MLA plane is \((s, t)\). When performing the just-stated operation, we are equivalently keeping \((u, v)\) fixed and counting every \((s, t)\) value.

**Figure 4 Schematic diagram of sub-aperture image extraction**
As indicated by Figure 4, perspective A means viewing the object from the uppermost part of the main lens aperture. Light rays that pass through perspective A will propagate to the same local pixels beneath the micro-lenses. The sub-aperture image A is obtained by aligning those pixels in a way that they are distributed on the MLA plane. The steps hold the same for perspective B to E. The total number of possible perspectives is equal to the number of pixels under a micro-lens, which is, in this case, represented as N-by-N. In practice, micro-lenses are circular, leading to a vignetting phenomenon that reduces the total number of usable perspectives. In conclusion, by applying rendering algorithms, multiple sub-aperture images can be obtained from one raw light-field image. It is worth noting that, there exists parallax between every two different sub-aperture images which will be taken advantage of in the later 3D reconstruction process.

3D reconstruction based on parallax

Epipolar constraint is applicable in the sub-aperture images extracted from a raw light-field image. By taking one certain row(or column) of pixels from sub-aperture images of the same row(or column) and stacking these rows of pixels, an epipolar plane image(EPI) is formed. Figure 5(a) shows one certain row(or column) of pixels and the corresponding EPI. In the EPI, slope values imply information about the depth of each sampled point. To give an intuitive explanation between EPI slopes and object depths, Figure 5(b) uses multiple traditional cameras aiming at the targeted object to signify multiple sub-aperture images. The images from each camera are given below. In the example EPIs, the red circle holds a positive slope value while the blue one has a negative slope. This can be interpreted as: the red circle is within the plane of focus(PoF) while the blue one is outside the PoF. The yellow circle is set right at the PoF that leads to a zero slope. Therefore, parallax can be quantified by calculating slopes on an EPI.

Figure 5(a) An example EPI of FCHs and (b) relation between EPI slope and object depth

Metric calibration

Figure 6 Propagation model of light inside a light-field camera
The camera metric calibration converts the magnitude of parallax to real physical depth. The way light propagates inside the camera system is shown in Figure 6. A bunch of rays emitting from point source P are refracted by the main lens and converge at point Q. They propagate forward and form a circle of confusion on the MLA plane (Ding, Li et al. 2019, Shi, Ding et al. 2019). The center is denoted as $C_{if}$ and its diameter is $D_{if}$. Then the light rays go across the MLA and eventually reach different pixels on the sensor plane, forming a projected circle of confusion. The center is denoted as $C_{df}$ and its diameter is $D_{df}$. Characteristics of a confusion circle $(C_{df}, D_{df})$ are solvable out of the scattered patterns on the image plane (Shi, Ding et al. 2019).

\[
(l_{p_j} - p_{ci})D_{df} + p_i \frac{s_i + f_i}{s_i} (l_{p_j} - C_{df}) = 0 \tag{1}
\]

where $l_{p_j}$ and $p_{ci}$ are micro-lens center and center of its scattered pattern respectively. $S_i$ is the image distance. $f_i$ is the focal length of the micro-lenses. In this case, metric calibration is performed through building a deterministic relation between the characteristics of the confusion circle and the point object.

Without loss of generality, the center of the main lens is set as the origin in this paper. The z-axis is set as the main lens axis that points outside the camera. In the light-field projection model, the main lens is regarded as a thin lens while the MLA is viewed as a pin-hole array model for simplicity. By applying Gaussian optics, a relation between the depth $P^z$ of object point $P(P^x, P^y, P^z)$ and its confusion circle diameter $D_{df}$ can be derived as:

\[
D_{df} = \frac{p_m(S_i + f_i)}{p_p}\left(\frac{S_i - f_m}{f_mS_i} - \frac{1}{p_z}\right) \tag{2}
\]

where $p_m$ is the effective main lens aperture and $f_m$ is the main lens focal length. $S_i$ is the object distance. $p_p$ is the pixel pitch. Point P, O, and Q are on the same line and the projected confusion circle center $C_{df}$ is on the extension line of POQ. Equations can be derived according to rules of similar triangles:

\[
C_{df}^u = \frac{s_i + f_i}{p_p}P^u + O_c^u \tag{3}
\]

\[
C_{df}^v = \frac{s_i + f_i}{p_p}P^v + O_c^v \tag{4}
\]

where $(C_{df}^u, C_{df}^v)$ denotes pixel coordinates of the projected confusion circle center and $(O_c^u, O_c^v)$ denotes the optical center of the confusion circle. Equations (2)-(4) establish a mapping relation between an object point and its confusion circle characteristics. Therefore, camera intrinsic parameters can be calibrated from images of a calibration board. The relation is exploited to convert parallax into depth. A 3D point cloud is obtainable as a result.

**EXPERIMENTAL MEASUREMENT OF FILM-COOLING HOLES**

**Experimental installation and procedures**

This paper includes a measurement test of some turbine blades to validate the proposed technique. As Figure 7 demonstrates, the measurement system consists of a monochrome industrial-grade light-field camera (VOMMA VA4300-M-CL, 7192x5432px), a composite main lens (AF Micro-Nikkor 200mm f/4D IF-ED and AF Nikkor 50mm f/1.4D mounted together by a 50-62 adapter ring), and a testing platform. The measurement procedures are:

1. Metric calibration. This investigation applied a volumetric calibration for a light-field camera (Shi, Ding et al. 2019). A calibration board with a 0.4mm dot array on it is placed on a high-precision translational stage (Thorlabs LNR50S /M, 0.1μm). The translation range covers 300μm in front of and behind the PoF. The translation step size is 20μm. There are a total of 31 positions where images are recorded. Relations between object points and their confusion circle characteristics are built out of raw calibration images.

2. Raw image capture. In Figure 7, the camera is placed downwards to capture images of the illuminated turbine blade (illumination omitted in Figure 7). The illumination is optimized by applying tiny bulbs or optical fiber according to the actual situation. Raw images are rendered and sub-aperture images are extracted. Parallax is quantified using EPI.

3. Parallax-to-depth conversion. The parameter obtained in step (1) is used to convert parallax (obtained in step 2) into real physical depth.

The whole process is accelerated by GPU. A point cloud with 436,000 points can be calculated with 5 seconds. The robustness of the measurement is only subject to different illumination strategies, which is rather a engineering problem that will not be included here.
Validation of accuracy

To validate the system accuracy, a set of standard gauge blocks whose thicknesses are 1.5, 1.6, 1.7, and 1.8mm are used. Procedures are implemented on these blocks in the same way as they are done on the turbine blade for 3D reconstruction. The blocks are labeled as ①②③④ respectively. Point clouds are calculated for each block. In Figure 8(b), different colors correspond to different depth value. This test has further validated measuring accuracy in a quantitative way. Depth value, i.e. the coordinate in z-axis, of the gauge block surfaces is measured by the proposed system. The plane with z = 0 is the plane of focus for the camera. In Table 1, the term absolute depth means the calculated depth which is averaged from a vast number of sample points on one of the surfaces. \( \Delta d \) and \( \Delta d' \) are the real and measured depth difference respectively. From Table 1, the overall measurement error is within 8%, which indicates the system is able to measure the geometry of FCHs with good accuracy.

![Figure 8](image)

**Figure 8 Validation of accuracy by imaging gauge blocks**

<table>
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<th>No</th>
<th>Absolute depth(mm)</th>
<th>( \Delta d )(mm)</th>
<th>( \Delta d' )(mm)</th>
<th>Percentage error(%)</th>
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<td></td>
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<td>0.0995</td>
<td>0.5</td>
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</tbody>
</table>

**RESULT AND ANALYSIS**

Limited by magnification, field of view, and current resolution of the light-field camera, the experiment only focuses on a local area with FCHs on it. Basic geometric parameters of a single FCH are described in Figure 9. \( \alpha \) is the exit angle. \( \beta \) is the deflection angle. S is the unilateral cross-section area. The main flow direction (depicted as an arrowhead in Figure 9) is not assigned, so the main measurable parameters are exit angle and cross-section area.
The measured data is shown in Figure 10(a). It is in the format of a colored point cloud from which FCH parameters are extracted. Though fitting the point cloud of one FCH, its axial direction can be derived which is displayed in Figure 10(b). The black inclined line indicates the hole axis. Viewing the unilateral local area as the surface that the main flow passes, exit angle can be calculated as the angle between axial direction and the surface orientation. In this case, the exit angle is $39^\circ5'$. Besides, by detecting edges on the center sub-aperture image and mapping the information onto the point cloud (see Figure 10(c)), the unilateral cross-section area can be calculated using `convhull` function in Matlab. In this case, the area is 0.826mm$^2$.

Notably, the measurement limitation in hole depth is greatly restricted by illumination. Data is lost where illumination is insufficient. This is also influenced by the accuracy of calculated exit angles. Moreover, the data measured here is based on the camera system. The coordinate system transformation should be considered if it involves practical engineering application.

CONCLUSIONS

This paper proposed a method for geometric measurement and inspection of film-cooling holes using co-axial light-field imaging. The technique uses one light-field camera and highly efficient algorithms to reconstruct 3D geometry of film-cooling holes. A set of standard gauge blocks are used to validate measurement precision, revealing an averaged system precision of less than 10μm. The single-light-field-camera solution has been applied in measuring a real blade with film-cooling holes on it. Exit angle and cross-section area are extracted. Although being unable to validate measuring accuracy in the real case due to the absence of ground truth data, the result has its reference value as it has proven the possibility of such a technique. The future work is to further combine engineering requirements with the technique and address more practical challenges.
ACKNOWLEDGMENTS

Many thanks to AECC Hunan Aviation Powerplant Research Institute for the provided device and guidance.

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