

## Article

# Fringe Projection Profilometry for Three-Dimensional Measurement of Aerospace Blades

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**Abstract:** The aero-engine serves as the “heart” of an aircraft and is a primary factor determining the aircraft’s performance. Among the crucial components in the core of aero-engines, aero-engine compressor blades stand out as extremely important. They are not only numerous but also characterized by a multitude of parameters, making them the most complex parts in an aero-engine. This paper aims to address the trade-off between accuracy and efficiency in the existing measurement methods for asymmetric blades. Non-contact measurements were conducted using a structured light system composed of a stereo camera and a DLC projector. The point cloud data of the blades are processed using methods such as the PCA (Principal Component Analysis) algorithm, binary search, and least squares fitting. This paper established a fringe-projection profilometry light sensor system for the multi-view measurement of the blades. High-precision rotary tables are utilized to rotate and extract complete spatial point cloud data of aviation blades. Finally, measurements and comparative experiments on the blade body are conducted. The obtained blade point cloud data undergo sorting and denoising processes, resulting in improved measurement accuracy. The measurement error of the blade chord length is 0.001%, the measurement error of blade maximum thickness is 0.895%, compared to CMM (Coordinate Measuring Machine), where the measurement error of chord is 0.06%.

**Keywords:** aero-engine blades; fringe projection profilometry; point cloud processing; blade assessment



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## 1. Introduction

Aero-engine blades, as one of the most crucial components of the engine, directly impact the efficiency and reliability of the entire engine through their design and performance [1,2]. With the aviation industry’s increasing emphasis on environmental impact and fuel efficiency, higher requirements are placed on the materials, design, and manufacturing technology of aero-engine blades. Blades are among the most precise and essential components of the engine, enduring high temperatures, pressures, and significant centrifugal forces. Their processing quality directly influences the overall efficiency, safety, and stability of the entire aircraft. In particular, the profiles design of the blades directly affects the engine’s efficiency, stability, and durability [3]. Therefore, the development of aero-engine blades has become a significant milestone in the progress of aviation technology. It centrally embodies cutting-edge technologies in various fields, including materials science, fluid mechanics, thermodynamics [4], and precision manufacturing.

In the aviation industry, the precise measurement of engine blades is a crucial step in ensuring their performance and reliability. With the continuous advancement of aviation technology, blade measurement methods are also constantly evolving and innovating to meet increasingly stringent accuracy requirements and challenges posed by complex shapes. Aero-engine blades are characterized by their diverse types, large quantities,

complex structures, high geometric precision requirements, and challenging manufacturing processes [5]. The processing precision and manufacturing level of engine blades are crucial factors influencing engine performance, safety, and lifespan. In order to ensure the normal performance of the engine, strict requirements are placed on the manufacturing precision of the blades, which must have precise dimensions, accurate shapes, and stringent surface integrity. Blade measurement primarily involves the assessment of characteristic parameters such as chord length, maximum thickness, and chord line. Additionally, with the development of various high-performance engines, there is a significant increase in demand for blades with different shapes, sizes, and surface qualities. This imposes higher requirements on blade measurement. Therefore, high precision and rapid measurement of blade surfaces are of great significance for improving blade processing quality and ensuring the performance of aero-engines [6,7]. For the measurement methods of the profiles of aero-engine blades, they can be broadly categorized into two types: contact measurement and non-contact measurement. Contact measurement typically refers to methods that use physical contact means to obtain surface data from the blades, with the most typical example being Coordinate Measuring Machines (CMMs) [8,9]. This type of method's main advantage lies in its high precision and reliability. Through the contact of a probing system with the blade surface, CMM can measure the geometric dimensions and shapes of the blades with extremely high accuracy. However, the drawback of contact measurement is its relatively slow speed, especially when dealing with complex or large blades [10,11]. Modern CMMs have the capability to move at high speeds, reaching several hundred mm/s. However, if accuracy is required, scanning typically needs to be conducted at slower speeds. To achieve acceptable accuracy on parts with tight tolerance, conventional scanning systems perform measurements at low speeds, usually less than 20 mm/s (0.8 in/s). Therefore, CMMs require approximately two hours to measure these blades. Non-contact measurement technologies include laser scanning, structured light scanning, and optical digitization. These methods involve using light or other radiation sources (such as X-rays) to measure the shape of blades without the need for direct contact with the blade surface. Song, X. developed an optical inspection device based on a flexible robotic arm for small compressor blades. Small compressor blades, typically blades with a chord length less than 70mm, are referred to as small blades. This device is utilized for detecting defects on the surface of AEB (Aero-engine Blade) during the production process [12]. This method enhances the measurement performance of small defects, but the measurement apparatus is relatively complex. Fringe projection profilometry is an advanced non-contact optical measurement technology commonly used for accurately measuring objects with complex geometric shapes, such as aero-engine blades. This technology combines structured light systems with binocular vision principles, enabling the precise reconstruction of the three-dimensional surface profiles of the measured object. Ma Kang Sheng [13] used a multi-frequency heterodyne-phase-shift method with an automatic positioning device for in situ measurement simulation, obtaining the original point cloud data of the blades. Ma Qian Li [14] proposed an algorithm for optimizing the selection of the optimal measurement angles in binocular-structured light, based on visual cones and vector optimization using measurement points. Using an industrial robotic arm to position the structured light at the selected measurement points, multi-view scanning measurements were conducted on aero-engine blades.

Liu X. developed a new technique combining composite stripe coding and stepped phase coding to solve high-quality absolute phase and realize deep learning-based binocular 3D profiles design reconstruction. The method only needs to project the composite stripe coding pattern to obtain the wrapped phase and the stepped phase coding pattern to obtain the stripe order, which solves the effects of defocus and noise on the deviation of wrapped phase and stripe order [15]. For the issue of fewer blade samples, a metric learning for the multi-output Gaussian process regression method (ML\_MOGPR) for aero-dynamic performance prediction of the plane cascade is proposed. It shares parameters between multiple output Gaussian distributions during training and measures the similarity between input

samples in a new embedding space to reduce bias and improve overall prediction accuracy [16]. For actively controlling non-linear blade vibrations, a rotating blade's non-linear oscillations are reduced via a time-delayed, non-linear saturation controller (NSC) [17].

After measuring and obtaining blade data, it is necessary to obtain blade characteristic parameters defined under standards for evaluation. Li, X. proposed an improved YOLOv5 method called DDSC-YOLO [18], which integrates several aspects, such as shape feature extraction, computational effort, and measurement performance. Ching Hin Lydia Chan [19] investigated the blade checkpoints' optimal distribution that will produce the most accurate B-spline fit to the surface of the CAD model, thus shortening the inspection and analysis process without compromising the accuracy. Jing-Jun Li proposed an ultrasonic defect in aero-engine blade point cloud [20] for quantitative evaluation, in which the regionally discretized defective point cloud is clustered into independent defective regions by the DBSCAN clustering algorithm. An averaged differential imaging method is presented and applied to the ultrasonic nondestructive evaluation of wind turbine blades [21]. In the image, we can successfully find line images with damaged parts, and we can estimate the depth of the damaged parts with high accuracy.

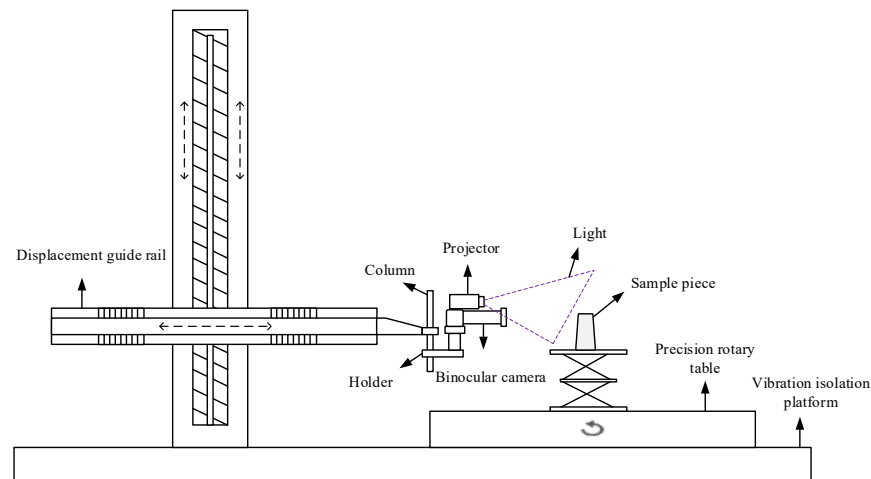
Generally, the methods for measuring blade profiles are more perfect at present, but the efficiency of the measurement will inevitably be reduced while ensuring the accuracy of the measurement. In this paper, we aim to solve the problem that the existing blade measurement scheme cannot balance accuracy and efficiency and will adopt a measurement system combining a fringe projection profilometry and a high-precision rotary table, which realizes the function of measuring a blade with high efficiency, precision, and stability. For the aero-engine blade parameters, a synchronized noise reduction algorithm based on the moving least squares method for sorting the blade's cross-section point cloud and a bifurcated search algorithm for mid-arc are proposed to fit the blade parameters, and the blade parameters are evaluated without the use of complex formulas to fit the blade profiles. Finally, several sets of comparison experiments with the CMM coordinate machine are conducted to verify that the accuracy meets the measurement requirements.

In this paper, we first obtained and unwrapped the phase containing the blade profile information based on the principle of the fringe projection profilometry method and utilized the spline difference for stereo matching. In order to integrate the measured data into the same coordinate system, the rotary table calibration method was proposed. In order to obtain the characteristic parameters of the blade, the cross-section of the blade was extracted using PCA analysis, the point cloud data were sorted, and the noise was reduced in order to improve the accuracy. Finally, the blade body was measured and evaluated against the standard values. In order to verify that the accuracy requirements were met, several sets of comparison experiments with the CMM were conducted, and the measurement requirements were met.

## 2. Measurement Principle

### 2.1. Measurement System Overview

The structure of the proposed measurement system based on fringe projection profilometry and an air-bearing rotary table is given in Figure 1. The sample of the asymmetric blade to be measured is mounted on a lifting table in the center of the rotary table with two degrees of freedom guide rails to adjust the horizontal as well as the vertical measurement position of the binocular-structured light sensor. The relative spatial relationship between the rotary table and the binocular-structured light sensor remains constant during the measurement process. A single measurement at a preset angular position and repeated measurements at equal intervals in conjunction with the rotation of the rotary table realize the multi-view rotational measurement of the blade.



**Figure 1.** Components and interconnection of the proposed measurement system.

The asymmetric blade measurement system is mainly composed of three parts: measurement device part, control and data processing part, and data interaction part. The measuring device mainly consists of a binocular-structured light sensor and a high-precision rotary table. The control and data processing section is an industrial-control computer system. The blade profile measurement needs to obtain the complete cross-section of the blade profile, so it is necessary to use a rotary table to extend the structured light measurement to multiple viewing angles; so, this paper designs a blade profile measurement system with a binocular-structured light and air-bearing rotary table.

## 2.2. Phase-Shift Method—Principle of Multi-Wavelength Phase Unwrapping

The phase-shifting method projects multiple pairs of phase-shifting sine fringe images within a cycle with a DLP projection camera, and then calculates the phase information of each pixel of the phase-shifting image. This phase information essentially encodes the height information, meaning that the height of the object's surface modulates the phase value. However, these phase details are wrapped within multiple cycles, hence referred to as the wrapped phase. By calculating the wrapped phase information, the height information of the object can be calculated. According to the mathematical model, the light intensity formula of the phase-shifting fringe image obeys the standard sine distribution as follows:

$$I(x, y) = A + B(\cos\varphi(x, y) + \Delta\varphi_k) \quad (1)$$

where  $A$  is the average gray scale of the image,  $B$  is the gray scale modulation of the image, and  $\varphi$  and  $\Delta\varphi_k$  are the relative phase code value and phase shift value, respectively. The overdetermined solution is computed by calculating the phase-shift equation in more than four steps. After calculating the final phase shift method, the parcel phase is calculated as follows:

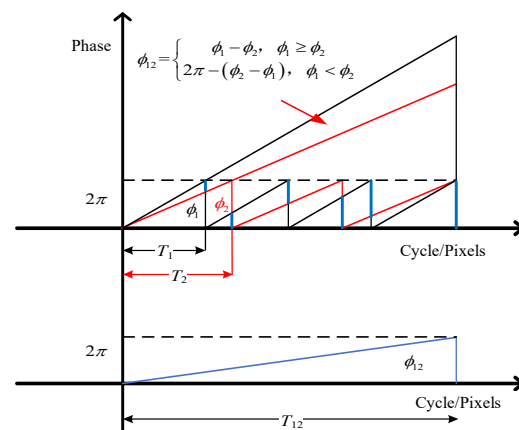
$$\varphi(x) = \arctan\left(\frac{B_2(x, y)}{B_1(x, y)}\right) = -\arctan\left(\frac{\sum_{k=0}^{N-1} (I_k \sin(\frac{2k\pi}{N}))}{\sum_{k=0}^{N-1} (I_k \cos(\frac{2k\pi}{N}))}\right) \quad (2)$$

The wrapped phase is the result obtained after the phase information is modulo  $2\pi$  operation. In the phase-shift method, different phase-shift images are obtained by multiple optical projections of the measured object, and these phase-shift images are processed by the above formula to finally obtain the wrapped-phase image of the measured object, and the phase-difference image can be obtained by subtracting two wrapped-phase images, thus realizing the calculation of the surface profile of the object.

For a higher measurement accuracy, this paper chooses the number of phase-shift steps  $N$  to be 12 and uses three modulation frequencies for phase expansion so as to minimize the

effect of nonlinear distortion. By using a set of phase-shift sequences containing 12 discrete phase-shift values, the original signal is phase shifted to obtain 12 phase-shifted signals. By performing amplitude ratio operations on these 12 signals, a wrapped-phase signal containing multiple phase jumps is obtained. Then, by unwrapping this wrapped-phase signal, the continuous phase information of the original signal can be obtained.

The basic Idea of the method is to obtain an alternate signal with a lower frequency by outperforming two sinusoidal signals with a small difference in frequency, thus realizing the phase unwrapping of the original signal. This method can effectively deal with signals whose phases contain a large number of phase cycles and improves the stability and accuracy of phase unwrapping. The mathematical principle of the dual-frequency outlier is shown in Figure 2.



**Figure 2.** Principle diagram of phase unwrapping using dual frequency heterodyne method.

The schematic diagram of the dual-frequency outlier principle is shown in Figure 2, where  $\varphi_1$  and  $\varphi_2$  are the phase functions of the two small cycles, while  $\varphi_{12}$  is the phase function of the larger cycle calculated by the outlier method of  $\varphi_1$  and  $\varphi_2$ , and its value is the least common multiple of  $\varphi_1$  and  $\varphi_2$ . Assuming that  $\varphi_1 < \varphi_2$ , the formula is as follows:

$$\varphi_{12} = \varphi_k - \varphi_2 \Rightarrow \frac{1}{T_{12}} = \frac{1}{T_1} - \frac{1}{T_2} \Rightarrow T_{12} = \frac{T_1 T_2}{T_1} \quad (3)$$

Similarly, based on the results of the dual-frequency outlier, the multi-frequency heterodyne can be calculated to achieve the effect of unfolding the global phase.

$$T_{23} = \frac{T_2 T_3}{T_3 - T_1} \quad (4)$$

$$T_{123} = \frac{T_{12} T_{23}}{T_{23} - T_{12}} \quad (5)$$

Therefore, the multi-frequency heterodyne method requires three different cycles of the parcel phase.

### 2.3. Cubic Spline Interpolation Subpixel Phase Value Stereo Matching Algorithm

The pixel values in the left and right views are interpolated by the cubic spline interpolation method, and the sub-pixel level matching results are obtained. The phase values of the pixels in the views obtained by the left and right cameras are calculated and interpolated by the sub-pixel matching results to obtain the phase values at the sub-pixel level. Based on the binocular camera parameters and the phase values, the 3D coordinates of the corresponding pixels are calculated. To obtain the 3D-point cloud data of the object surface, the 3D coordinates for all pixels are calculated.

The main advantage of the stereo matching algorithm for sub-pixel phase values based on cubic spline interpolation is that it can make full use of the sub-pixel level information between pixels, thus improving the measurement accuracy. Meanwhile, the use of cubic spline interpolation can make the interpolation results smoother and avoid unnecessary noise caused by interpolation errors. The mathematical principle of cubic spline interpolation is as follows: let the pixel horizontal coordinates of the interpolated point be  $x_0, x_1, \dots, x_n$ , and the corresponding phase values be  $y_0, y_1, \dots, y_n$ . A cubic polynomial is used to approximate the interpolated point in the following form:

$$s_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3, x_i \leq x \leq x_{i+1} \quad (6)$$

where the four coefficients  $a_i, b_i, c_i, d_i$  can be determined by the following constraints:

- (1) The function is equal to the known value at each interpolation point, i.e.:

$$s_i(x_i) = y_i \quad (7)$$

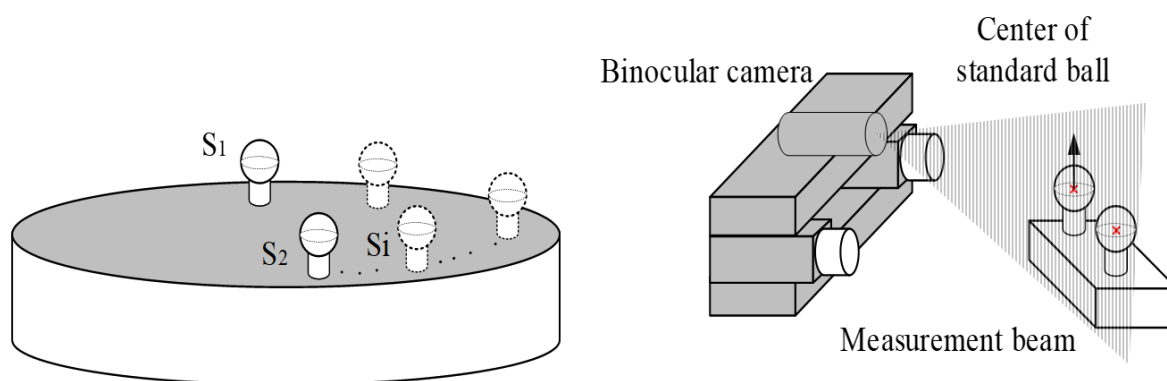
- (2) The first and second order derivatives of the function at the two end points  $x_i$  and  $x_{i+1}$  of the interpolation interval are equal, i.e.:

$$s_i^{(k)}(x_i) = s_{i-1}^{(k)}(x_i), s_i^{(k)}(x_{i+1}) = s_{i+1}^{(k)}(x_{i+1}), k = 0, 1, 2 \quad (8)$$

Computationally, in order to solve  $a_i, b_i, c_i, d_i$ , a system of linear equations needs to be constructed, and in order to simplify this problem, iterative solution methods are often used to approximate the solution of the system of equations.

#### 2.4. Calibration Method of Relative Position of Rotary Table

In order to integrate all measurements of the blade into the same coordinate system, a standard sphere is used to determine the spatial attitude of the turntable. A standard sphere is configured on the turntable for rotational scanning. A binocular-structured light sensor scans the sphere defined on the turntable to obtain the center position of the sphere at each measurement position. The positions are determined by illuminating the standard sphere using data from the measurement portion of the binocular-structured light beam. As shown in Figure 3,  $S_1, S_2, \dots, S_i$  are the measurement positions and  $i$  is the number of measurements. A schematic diagram of the rotary table calibration device is shown in Figure 3.

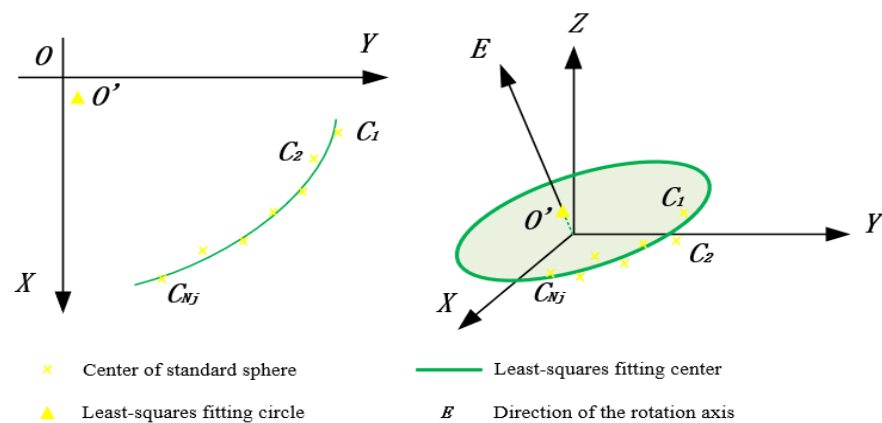


**Figure 3.** Diagram of experimental setup for turntable calibration.

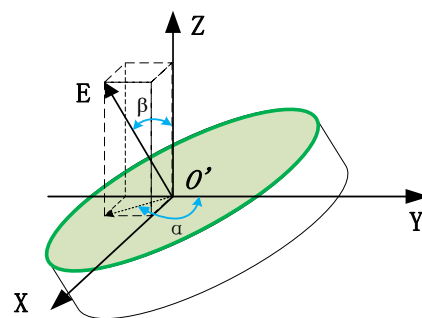
As shown in Figure 4, the fitted center  $O' (x_0, y_0, z_0)$  and normal vectors  $E (a, b, c)$  of the sequence  $c_1 \sim c_{Nj}$  are obtained using the least squares fitting method. As shown in Figure 5,  $O'$  and  $E$  are the center and direction of the rotation axis, respectively. Here,

$E(a, b, c)$  is reduced to two parameters,  $\alpha$  and  $\beta$ . The angle  $\alpha$  starts from the positive direction of the y-axis and rotates counterclockwise.

$$\begin{cases} \alpha = \begin{cases} \arccos\left(\frac{b}{\sqrt{a^2+b^2}}\right), & a \geq 0 \\ 2\pi - \arccos\left(\frac{b}{\sqrt{a^2+b^2}}\right), & a < 0 \end{cases} \\ \beta = \arccos\left(\frac{c}{\sqrt{a^2+b^2+c^2}}\right). \end{cases} \quad (9)$$



**Figure 4.** Determination of the axis center  $O'$  ( $x_0, y_0, z_0$ ) and normal vector  $E(a, b, c)$ .

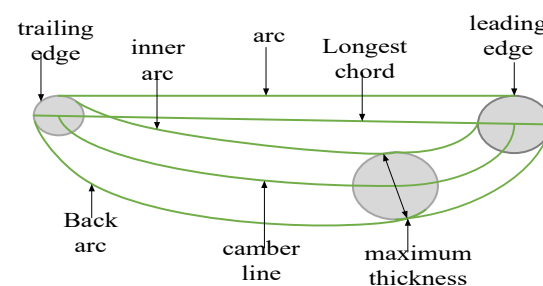


**Figure 5.** Spatial direction  $E$  of the axis of the rotary table.

### 3. Measurement Method

#### 3.1. Definition of Blade Body Characteristic Coefficients

According to the industrial standard, the parameters to be extracted from the blade body are shown in Figure 6:



**Figure 6.** Blade profile parameters.

In this paper, the blades we measured are made of high-temperature nickel-based alloy. Several parameters that have the greatest impact on the performance of aero-engine blades are selected for evaluation: chord, chord length, mid-arc, and maximum thickness of the blade. Their definitions are shown in Table 1.

**Table 1.** Names and definitions of blade body characteristic parameters.

| Parameter                          | Definition                                                                   |
|------------------------------------|------------------------------------------------------------------------------|
| cord                               | A straight-line tangent to both the leading and trailing edges of the blade  |
| chord length                       | The maximum length of the blade cross-section in the chord direction         |
| camber line                        | The line connecting the maximum inscribed circle center of the blade section |
| Maximum thickness of blade profile | The diameter of the tangential circle within the blade section               |

### 3.2. Extraction of Blade Cross Sections by PCA Method

In this paper, a Principal Component Analysis (PCA algorithm) is used to determine the benchmarks for the evaluation of the measurement data. The PCA algorithm is a set of linearly uncorrelated variables converted into a set of variables that may be correlated by orthogonal transformation, so that multiple variables in the data are independent of each other, and the converted variables are called principal components. For point cloud data, the principal components represent the degree of dispersion between the three coordinates, and the PCA algorithm establishes the characteristic coordinate system by the direction with the largest variance of the point cloud coordinates. The direction with the largest variance of point cloud coordinates is the Z-axis of the blade; thus, the PCA algorithm can be used to determine the base coordinate system of the measurement data. The main process of the PCA algorithm is as follows:

(1) Calculate the center of mass position of the point cloud.

Let the blade-point cloud data be  $C = \{P^1, \dots, P^N, P^n = (x_n, y_n, z_n)\}$ , then the point cloud center of mass  $m = (\bar{x}, \bar{y}, \bar{z})$  is given by:

$$m = \frac{1}{N} \sum_{n=1}^N P^n = \left( \frac{1}{N} \sum_{n=1}^N x_n, \frac{1}{N} \sum_{n=1}^N y_n, \frac{1}{N} \sum_{n=1}^N z_n \right) \quad (10)$$

(2) Calculate the covariance matrix.

Covariance of the two axes  $cov(x, y)$  representing the point cloud data distribution correlation in these two axes, the formula is as follows:

$$cov(x, y) = cov(y, x) = \frac{1}{n-1} \sum_{i=1}^{n-1} (x_i - \bar{x})(y_i - \bar{y}) \quad (11)$$

The covariance matrix  $C$  is calculated as follows:

$$C = \begin{bmatrix} cov(x, x) & cov(x, y) & cov(x, z) \\ cov(y, x) & cov(y, y) & cov(y, z) \\ cov(z, x) & cov(z, y) & cov(z, z) \end{bmatrix} \quad (12)$$

Compute the PCA transformation matrix.

Let the eigenvalues of the covariance matrix  $C$  be  $\lambda_1, \lambda_2, \lambda_3$ , and  $\lambda_1, \lambda_2, \lambda_3$ ; and let the corresponding eigenvectors be  $e_1, e_2, e_3$ , respectively. Then, the chi-square coordinate transformation matrix  $T_{PCA}$  is formulated as follows:

$$T_{PCA} = \begin{bmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \\ 1 \end{bmatrix} \quad (13)$$

The coordinates of the transformed point cloud are  $C_{PCA} = T_{PCA}C$ .

### 3.3. Point Cloud Processing and Noise Reduction Sorting

In order to evaluate the cross-section features subsequently, the point cloud needs to be partitioned, and the ordered point cloud can effectively improve the efficiency of the subsequent noise reduction and partitioning algorithm. During the measurement process, due to the angle between the structured light and the main direction of the blade, it is not possible to measure the complete and organized cross-section line data within the same measurement. When the fringe projection profilometry is used to measure the point cloud of the blade, the number of noise points is large, and the result of processing the point cloud will have a great impact; so, it is necessary to perform noise reduction and smoothing filtering on the original point cloud data collected.

The basic steps of the aero-engine blade sequencing synchronous noise reduction method based on the moving least squares method proposed in this paper are as follows:

(1) Weight selection: Select the appropriate threshold  $H$ . Starting from the first point of the original data, which is also the first point after sorting, set this point as the current point with serial number  $i$ , transverse the remaining point  $p_j$ , calculate its distance  $r$  from this point, and the weight of the remaining point is:

$$w_j = e^{-\frac{r^2}{H^2}} \quad (14)$$

(2) Coordinate transformation: Fit a local least squares line with the weights and compute a rotation matrix to rigidly transform the entire cross-section point cloud to a new coordinate system with the line as the x-axis and the current point as the origin.

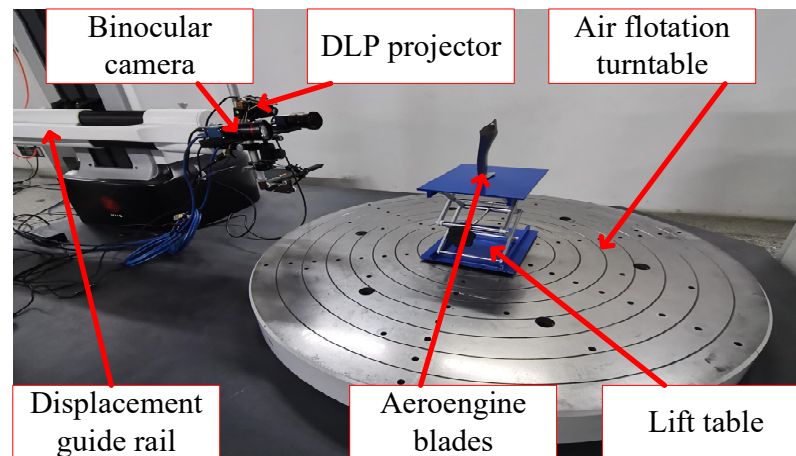
(3) Noise reduction: Recalculate the weights of the remaining points after the transformation is completed, fit the parabola with the new weights and replace the current point with the intersection of the parabola and the y-axis of the current coordinate system.

$$w_j = \begin{cases} \frac{2r^3}{H^3} - \frac{3r^2}{H^2} + 1 & r \leq H \\ 0 & r > H \end{cases} \quad (15)$$

(4) Sorting: Using the current coordinate system as a reference, the x-axis in a positive direction from the origin of the nearest point for the  $i + 1$  point, as shown in the blue line, represents the current order of connection. The left side of the red circle points to complete the sorting, and the right side is to be sorted. Repeat steps (1) to (4).

## 4. Experiments

When using fringe projection profilometry to obtain the point cloud of the blade, the number of noise points is large, and it has a significant impact on processing the point cloud. Therefore, it is necessary to perform noise reduction and smoothing filtering on the collected raw point cloud data. First of all, the measurement system is constructed by using a binocular-structured light sensor and high-precision rotary table, and the relative position between the sensor measurement coordinate system and the relative position of the rotary table in the measurement coordinate system are calibrated; then, the aero-engine blade is measured, and the blade profile parameters are obtained from the specified profile after the data splicing, processing, and blade profile characteristic parameter extraction. The blade profile parameters are measured by scanning the measurement system are compared with the three coordinate measurement results to verify the effectiveness of the measurement method proposed in this paper. Finally, the blade parameters measured by the scanning measurement system are compared with the CMM results to verify the effectiveness of the measurement method proposed in this paper. The physical diagram of the blade measurement system is shown in Figure 7.



**Figure 7.** Physical diagram of blade measurement system.

The measurement system utilizes two cameras with dimensions of  $36 \text{ mm} \times 31 \text{ mm} \times 38.8 \text{ mm}$ , and the specific parameters of the cameras are listed in Table 2 below.

**Table 2.** Digital camera parameters.

| Frame Rate | Pixel Count     | Pixel Size                               | Pixel Depth   | Exposure Time                     |
|------------|-----------------|------------------------------------------|---------------|-----------------------------------|
| 15.1 fps   | 26,200 thousand | $2.5 \mu\text{m} \times 2.5 \mu\text{m}$ | 8 bit, 12 bit | $11 \mu\text{s} \sim 1 \text{ s}$ |

#### 4.1. Calibration Experiment

An air-float rotary table and a binocular-structured light sensor are used as the main equipment of the proposed measurement system. As shown in Figure 8, a standard sphere is used for the calibration experiment. The standard sphere is placed on the descending table and the air-bearing turntable is rotated by  $30^\circ$  to obtain a set of point clouds of the sphere. As shown in Figure 9, the left and right panels are the pictures obtained by photographing the standard sphere during the calibration of the binocular camera, respectively. The least squares method was used to determine the fitting center  $O'$  ( $x_0, y_0, z_0$ ) and the fitting plane, which are equal to  $Zo'$  ( $-21.5382, 0.0423, 1.1557$ ) mm and  $-0.4428x + 0.0206y - z = 8.3823$ , i.e.,  $\alpha = 272.6578^\circ$  and  $\beta = 156.0973$ , and the method described in Section II-D is used to compute the central sequence of the standard spheres  $C_1 \sim C_J$  in conjunction with the radius of the reference sphere.

We utilized a standard sphere with a known center-to-center distance of 100.125 mm for the turntable calibration experiment. The turntable calibration results were validated by moving the turntable and measuring the standard sphere multiple times. The point cloud data obtained from multiple measurements were stitched together using the turntable calibration results. The fitted sphere center distance was then compared with the known standard sphere center distance. The results, as shown in Table 3, indicate a final measurement error of 0.0329 mm for the sphere center distance, meeting the measurement requirements. The table depicting the tolerance of the blade contour is presented in Table 4.

**Table 3.** Turntable calibration experiment.

| No. | Distance (mm) | Error (mm) |
|-----|---------------|------------|
| 1   | 100.1077      | 0.0172     |
| 2   | 100.1387      | 0.0137     |
| 3   | 100.2         | 0.075      |
| 4   | 100.169       | 0.0439     |
| 5   | 100.1102      | 0.0147     |
| Avg | 100.14512     | 0.0329     |

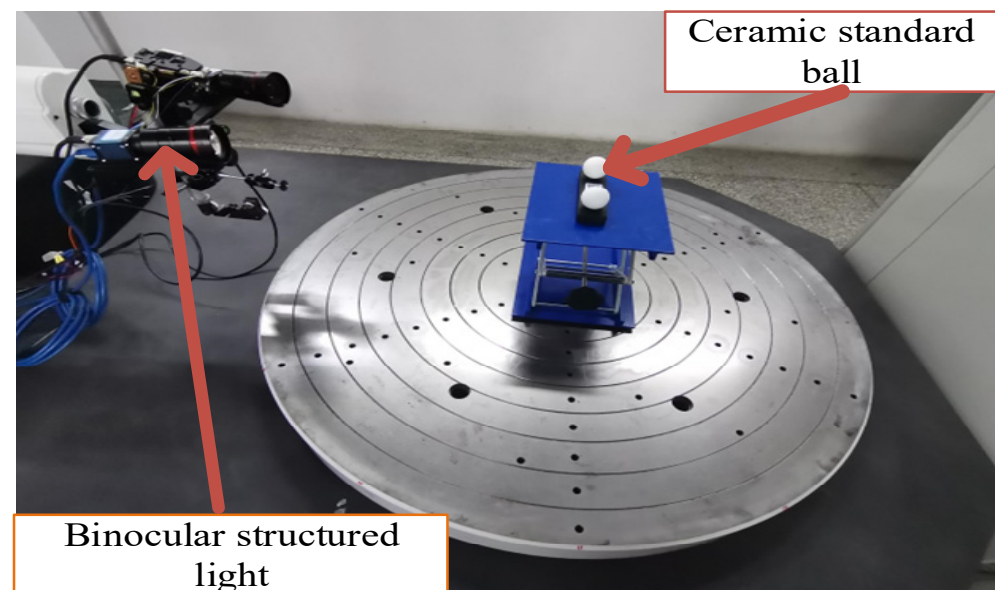


Figure 8. Conduct calibration experiments using a pair of standard spheres.



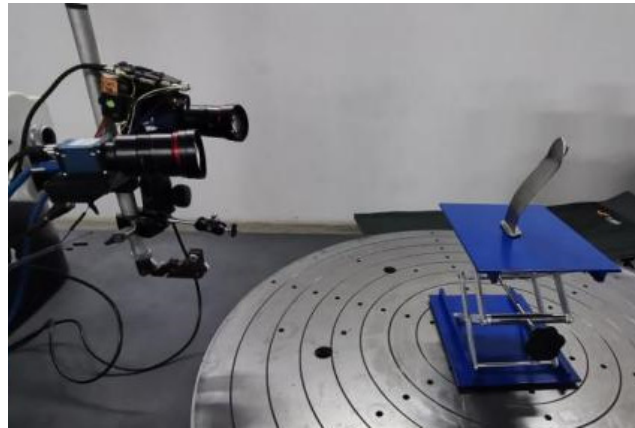
Figure 9. Phase map captured by left and right cameras.

Table 4. Tolerance of blade contour.

| Nominal Size of Chord Length (mm) | Accuracy Grade | Compressor Blades |            | Turbine Blades |            |
|-----------------------------------|----------------|-------------------|------------|----------------|------------|
|                                   |                | Edge              | Midsection | Edge           | Midsection |
| $\leq 16$                         | 1              | 0.05              | 0.05       | 0.10           | 0.13       |
|                                   | 2              | 0.06              | 0.06       | 0.13           | 0.16       |
|                                   | 3              | 0.08              | 0.08       | 0.16           | 0.20       |
|                                   | 4              | 0.10              | 0.10       | 0.20           | 0.25       |
| >16~25                            | 1              | 0.05              | 0.06       | 0.13           | 0.16       |
|                                   | 2              | 0.06              | 0.08       | 0.16           | 0.20       |
|                                   | 3              | 0.08              | 0.10       | 0.20           | 0.25       |
|                                   | 4              | 0.10              | 0.13       | 0.25           | 0.31       |
| >25~40                            | 1              | 0.06              | 0.08       | 0.16           | 0.20       |
|                                   | 2              | 0.08              | 0.10       | 0.20           | 0.25       |
|                                   | 3              | 0.10              | 0.13       | 0.25           | 0.31       |
|                                   | 4              | 0.13              | 0.16       | 0.31           | 0.40       |
| >40~64                            | 1              | 0.06              | 0.10       | 0.16           | 0.25       |
|                                   | 2              | 0.08              | 0.13       | 0.20           | 0.31       |
|                                   | 3              | 0.10              | 0.16       | 0.25           | 0.40       |
|                                   | 4              | 0.13              | 0.20       | 0.31           | 0.50       |

#### 4.2. Blade Body Measurement and Evaluation

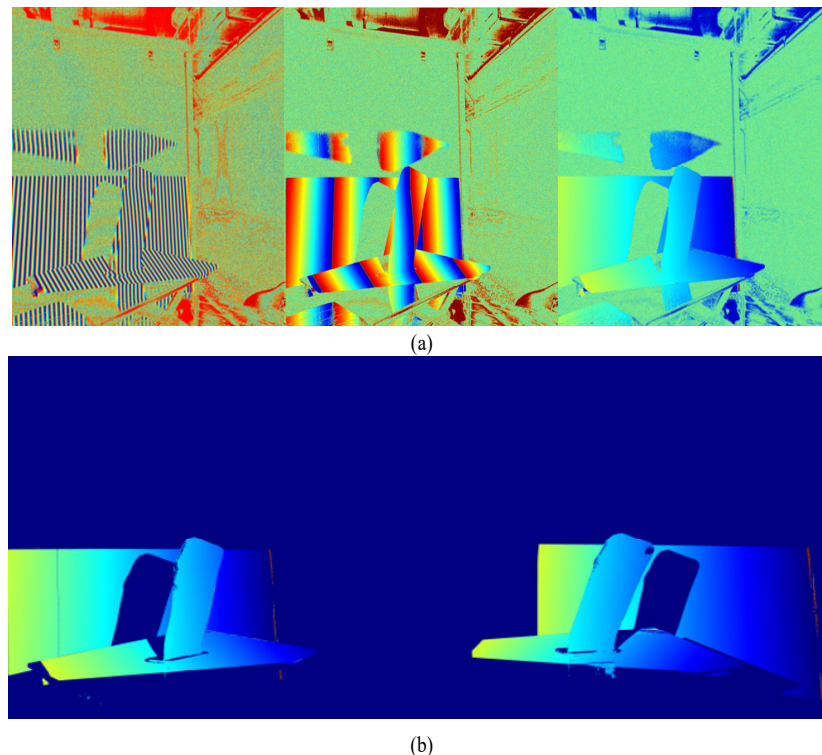
Measurement blades are shown in Figure 10.



**Figure 10.** Measuring blade.

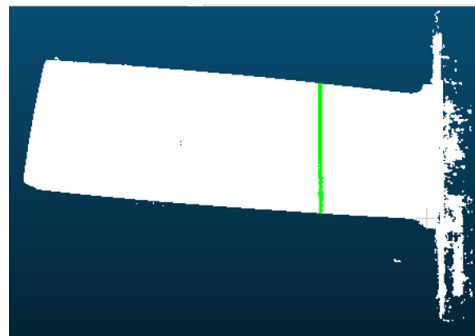
After the calibration of the measurement system is completed, the blade scanning measurement is carried out. The blade is adjusted so that it lies within the measurement range of the binocular camera, the appropriate sampling interval for the structured light sensor is set, and measuring from the front side of the blade begins until the entire blade contour is measured. After the blade profile measurement is completed, the splicing of the structured light sensor measurement profile is completed according to the results of the rotary table movement direction calibration, and the whole splicing process is based on the initial measurement position of the blade.

The phase-shift method—principle of multi-wavelength phase unwrapping method described in Section 2.2 is used to calculate the parcel phase, and the results are shown in Figure 11. As shown in Figure 11, the transition from red to blue represents phase values from high to low. According to the discussion in Section 2.2, for this experiment, we chose  $T_1 = 28$ ,  $T_2 = 26$ ,  $T_3 = 24$ , in units of the pixels of the projection light engine. It can be observed from the figure that accurate phase unwrapping has been achieved, resulting in a well-preserved global phase.



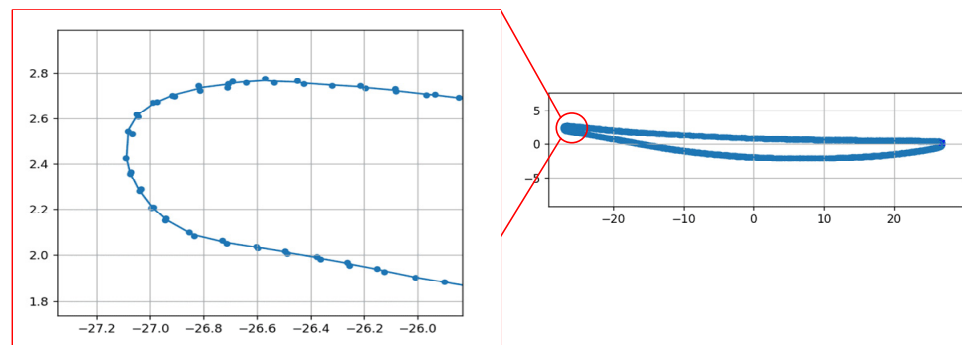
**Figure 11.** (a) Multi-frequency heterodyne unpacking. (b) Adjustment chart.

The PCA principal component analysis method described in Section 3.2 is used to determine the benchmark for measurement data evaluation. After repeated measurements through the rotary turntable to obtain the original point cloud after pre-processing and multi-view scanning of the aero-engine blade, in order to extract the final parameters, the cross-section needs to be extracted. The blade cross-section point cloud extraction algorithm is used, and the PCA algorithm is used to align the original point cloud of the aero-engine blade to the datum. The scanned point cloud is aligned to the original point cloud by the global matching algorithm, as shown in Figure 12, and the white point cloud is the scanned point cloud. The original point cloud, after the alignment of the cross-section projection, takes two intervals of 0.3 mm perpendicular to the PCA alignment of the coordinate system after the Z-axis of the plane interception figure in the green area of the cross-section of the point cloud, as shown in Figure 12.



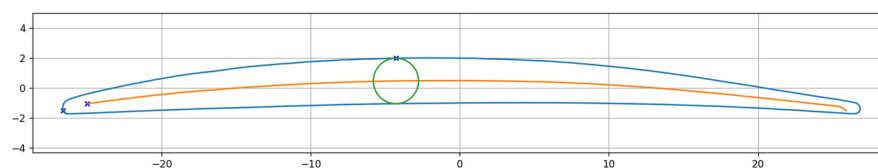
**Figure 12.** Extraction results of aero-engine blade cross-section.

In order to accurately extract the parameters, the cross-section is filtered, noise is reduced, and the 2D-point cloud of the height section is sorted at the same time, as shown in Figure 13.



**Figure 13.** Synchronous noise reduction results of aero-engine blade section sorting.

The parabolic segmentation method is used for the blade basin and blade dorsum to segment the blade basin and blade dorsum, after extracting the mid-arc by the bisecting search method, as shown in the orange curve in Figure 14, and the inner tangent circle at the maximum thickness is shown in the green circle in Figure 14.



**Figure 14.** Search results for midline and maximum blade thickness.

The results of this are evaluated on two parameters: chord length and maximum thickness. Random cross-sections of different heights were evaluated, and the error of the maximum thickness was 0.096 mm. The experimental data are shown in Tables 5 and 6 below.

**Table 5.** Chord length measurement results.

| Chord Length Reference | Mean Measurements Value | Difference Value |
|------------------------|-------------------------|------------------|
| 54                     | 53.9232                 | 0.142%           |
| 53.75                  | 53.7176                 | 0.060%           |
| 53.5                   | 53.4992                 | 0.001%           |
| 53.25                  | 53.2459                 | 0.008%           |
| 53                     | 52.9994                 | 0.001%           |

**Table 6.** Maximum thickness measurement results.

| Maximum Thickness Reference Value | Mean Measurements Value | Difference Value |
|-----------------------------------|-------------------------|------------------|
| 2.8                               | 2.82178                 | 0.778%           |
| 2.9                               | 2.94716                 | 1.626%           |
| 3                                 | 3.03024                 | 1.008%           |
| 3.1                               | 3.11484                 | 0.479%           |
| 3.2                               | 3.1813                  | 0.584%           |

#### 4.3. Comparative Blade Profiles Experiment

In order to verify whether the accuracy of the measurement system can meet the requirements, a comparative experiment on the same set of blades was carried out with a CMM, which is currently known to have a high measurement accuracy. The blades were fixed on a rotary table, and the CMM probe was contacted to obtain 3D data of the blades.

A least squares fit was used to fit the cross-section of the blade at a certain height and the comparison data are shown in Table 7 below. The precision of the coordinate measuring machine (CMM) we used is within 1 micron.

**Table 7.** Comparison results.

| No. | Chord Measurement |        |       |
|-----|-------------------|--------|-------|
|     | CMM               | Camera | Error |
| 1   | 52.796            | 52.770 | 0.05% |
| 2   | 52.815            | 52.764 | 0.10% |
| 3   | 52.715            | 52.771 | 0.11% |
| 4   | 52.743            | 52.762 | 0.04% |
| 5   | 52.812            | 52.763 | 0.09% |
| 6   | 52.754            | 52.759 | 0.01% |
| 7   | 52.722            | 52.774 | 0.10% |
| 8   | 52.782            | 52.755 | 0.05% |
| 9   | 52.716            | 52.773 | 0.11% |
| 10  | 52.767            | 52.762 | 0.01% |
| Avg | 52.762            | 52.765 | 0.01% |
| Std | 0.039             | 0.006  |       |

## 5. Conclusions

This paper proposes a blade profile measurement method based on fringe projection profilometry and a rotary table. The measurement system adopts a binocular camera to ensure that the measurement accuracy meets the requirements while effectively improving the measurement efficiency of the blade. The method makes full use of the advantages of fringe projection profilometry to reconstruct the overall macroscopic shape information of

the blade surface and carries out a multi-view profile measurement of the blade through the rotary table. Such a combination can overcome the problem of insufficient accuracy of fringe projection profilometry at the microscopic scale. The results of our study can be summarized as follows:

- (1) Completed the establishment of the fringe projection profilometry system and the air flotation rotary table model, according to the model to achieve the rotary motion control of the blade; the use of fringe projection profilometry with its high precision, high resolution, and high efficiency maximize the degree of simplification of the measurement process, and at the same time to meet the requirements of precision.
- (2) Aiming at the nonlinear displacement problem of the projector, in order to reduce the nonlinear error of the projector, a wrapped-phase calculation method based on the twelve-step phase-shift method is proposed, which improves the accuracy of the wrapped-phase solution, and a phase-unwrapping algorithm based on the multi-frequency outlier method is adopted, which reduces the problem of the phase cycle hopping error from the principle, and improves the accuracy of phase unwrapping.
- (3) A simultaneous noise-reduction–sorting algorithm is proposed. Noise reduction is accomplished while sorting, and uncomplicated formulas can be used to fit the surface of the blade and the point cloud can be rated directly. The study of sorting and noise reduction algorithms on the blade cross-section is accomplished, and the experimentally obtained point cloud data of the blade cross-section are filtered out of the noise.
- (4) Measurement and comparison experiments are carried out on the blade, and the accuracy of the binocular system measurement is verified using the CMM, and the maximum error of the blade maximum thickness measurement is verified to be 1.626% through experiments. A chord search algorithm was proposed to extract the chord and the chord length, the maximum error of the chord length extraction is verified to be 0.142% through experiments, and the error of the CMM is 0.06%.

**Prospect:** In this paper, the aero-engine blade profile has been investigated, but there are still some aspects that need to be investigated in more depth, for example, the sensitivity to ambient light and reflections on specific surface materials. Aero blades are usually made of metal or are coated with reflective materials, which may lead to high reflections of structured light on the blade surface, thus interfering with the measurement accuracy. Subsequent polarization filters may be used, or special surface treatment techniques may be applied to reduce reflections. Ambient light in laboratory or factory environments may interfere with the projection and capture of structured light, and we can only control the ambient light conditions by using filters or making measurements in darker environments.

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