DEVELOPMENT AND APPLICATION OF BLADE INSPECTION SYSTEM BASED ON MULTI-OPTICAL SENSOR FUSION

Yanyan Guo[1], Xiangli Meng[2],Ying He[1], Hongjun Zhang[1]*
[1]School of Mechanical and Electrical Engineering, Lingnan Normal University, ZhanJiang, 524048, China
[2] School of Electronic and Electrical Engineering, Lingnan Normal University, ZhanJiang, 524048, China
E-mail: guoyy1@lingnan.edu.cn; https://orcid.org/0000-0003-4159-6624

Abstract - Blades are critical components that determine the energy conversion efficiency of an aeroengine. The size of the blade profile and the surface quality must meet the requirements of high strength and reliability. Therefore, precision inspection and quality control are important in manufacturing and assembly. However, the technical characteristics of blades, such as complex profile, thin and distorted structure, high manufacturing accuracy and so on, make the measurement of blades difficult. Existing measurement and inspection methods based on high-precision three-coordinate measurement machine (CMM) and a single optical sensor have obvious technical limitations, which are difficult to satisfy of rapid measurement speed, high accuracy and data integrity of aviation blade profile, and more difficult to achieve accurate measurement of the inlet and exhaust edges. In view of the above problems, this paper studies the measurement method of aviation blade based on the fusion of optical sensors with different principles, and gives full play to the advantages of holographic interferometry and structural scanning, and develops a set of precise and rapid three-dimensional measurement system of aviation blade based on the combination of fringe projection profilometry and conoscopic holography. The measurement experiments and results show that the developed measurement system has high measurement speed and accuracy, and has great potential for popularization and application.

Keywords: Multi-optical sensor, Blade inspection system, Conoscopic holography, Fringe projection profilometry, Fusion.

1. Introduction

Blades are the core components of turbine machinery such as aero-engine and generator turbine. they usually work in harsh environment of high temperature and high pressure, and are the parts with high failure rate in the engine [1-3]. To satisfy the high strength and high reliability of the turbine blade after production, the size and surface quality of the blade after manufacturing must be strictly guaranteed [4]. Therefore, the quality inspection in the design and manufacturing process is very important [5-7].

At present, blade profile parameters are mainly measured using the template method, the three-coordinate method (adopting a CMM), and the optical method [2]. The template method is generally used for quality control with low accuracy. The detection accuracy of the template method is greatly affected by human factors, and it is thus difficult to manufacture high-precision templates. The final inspection means is a CMM, which is well-known high-precision technology. However, in the measurement of the complex surface of a blade, a cosine error is generated in the process of the probe radius compensation process.

Moreover, the measurement is slow and is usually made only for inspection of the blade section curve. With the rapid development of optics and computing technology, the optical method has been gradually introduced into the field of high-precision measurement [5,6]. Structured light scanning [8] and holographic interferometry [9] have been increasing-ly applied. Among them, the structured light scanning method directly measures parts with high reflective surfaces through the adoption of algorithms and technologies such as input light intensity control and exposure and angle optimization [8,10], and its measurement efficiency reaches 10 million points per second. However, its accuracy is low, and the measurement of leading/trailing edges is difficult or even impossible. Conoscopic holography (CH) is a technology that is used to directly measure a highly reflective surface with high accuracy [9,11]. Mounted on a multi-axis precision motion platform, this technology accurately measures the surfaces and leading/trailing edges of blades, but it has low measurement efficiency.

As described above, the development of blade detection has trended toward optical measurement. However, a single optical measurement method has the obvious technical limitation that it is difficult to measure an aviation blade surface with high speed and precision [12].

Many researchers have investigated integrated measurement methods that adopt inhomogeneous sensors to make full use of technical advantages to realize rapid and accurate full-scale measurements [12,13]. Such integrated measurement methods usually use one or more independent heterogeneous sensors to drive one or more other sensors to collect information of the object. A typical case of integrated measurement application is the integration of a non-contact structured light sensor into a CMM, where the structured light sensor is responsible for the fast acquisition of three-dimensional (3D) data and the contact probe obtains higher measurement accuracy. Meanwhile, the structured light sensor is used to obtain the global information of measured parts to guide and drive the high-precision contact probe in acquiring high-precision coordinate data [14,15]. Various optical measurement methods well complement each other for an inspection task performed at multiple scales and resolutions. In order to measure the tool wear state more accurately, Weckenmann et al. [16] fused fringe projection and white light interferometer to build a measuring system for cutting tools. SoKolov et al. [17] developed a nano-scale three-dimensional measurement system based on confocal sensing and contact probe. Ren et al. [18] put up a multi-sensor fusion system to efficiently measure multi-scale complex surfaces by integrating the technical advantages of CMM and photometric stereo. Xiang et al. [19] proposed a fusion measurement system that can eliminate system errors. The system is composed of a laser scanner and a touching probe.

As far as we know, there is no special integrated 3D measurement method for obtaining the 3D shape of blades. To realize the accurate and rapid measurement of a blade, this paper proposes a nonuniform optical 3D measurement method combining fringe projection profilometry (FPP) and CH. The proposed method takes advantage of the fast 3D data acquisition ability of FPP to measure the blade surface, uses the 3D data to drive holographic interference, adopts CH sensor to sample points on the blade surface and measure the leading/trailing edges, and fuses complete 3D data. This integration may be the best solution in terms of accuracy and efficiency.

2. System Setup

2.1 CH Sensor

The CH sensor is a non-contact point-based range sensor that measures distances by using the polarization properties of a converging light cone that reflects from an object [20]. The technology uses an anisotropic crystal to split the light passing through the crystal into two beams with orthogonal polarization that share the same path, creating a phase difference interference pattern. The distance is calculated by analyzing the interference pattern. The base principle is depicted in Figure 1.

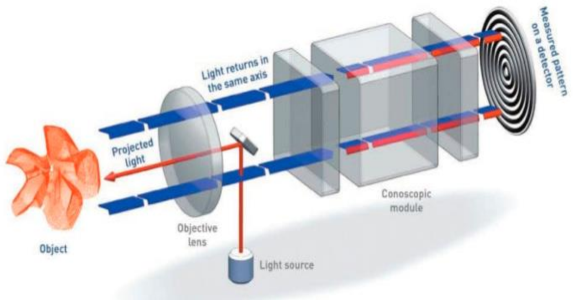

Figure1: Principle of conoscopic holography method

The CH sensor used in this article is manufactured by Optimet in Israel. It has the modular setting of interchangeable objective lens, which can realize different working ranges of the same sensor. Compared with the traditional triangulation method, when integrated in the measuring equipment, the conoscopic technology provides the main advantages, such as low electronic noise, high accuracy, and multiple standoffs [21]. The main technical parameters of the sensor are shown in Table 1.

Table 1. The parameters of sensor

Focal length	16	25	40	50
Accuracy(μm)	<2	<3	<4	<6
Repeatability (μm)	<0.15	<0.4	<0.7	<1
Measuring range(mm)	0.6	1.8	4	8
Distance from the part (mm)	9.5	14	43	44
Angle (°)	150°		170°	
later resolution (μm)	5	12	14	15
Spot size（μm）	16	18	25	26
Scanning speed	9000points/second			

Selecting different focal lenses can achieve measurement tasks with different accuracy. The corresponding measurement distance, depth of field and measurable angle also varies with the focal lens. The advantages of CH sensor are high measurement accuracy, large measurement range and angle (up to 170 degrees), and can directly measure highly reflective and bright surfaces; The disadvantage is that the measurement distance and depth of field are small when achieving high-precision measurement.

When measuring with this probe, there are two key parameters to be set:

(1) Working frequency. This value represents the number of measuring points that can be obtained by the probe in unit time, that is, the scanning sampling speed in Table 1, which can reach up to 9000 points/second (9000Hz).

(2) Power Level. This value represents the energy of the laser beam output by the probe. The setting range is 0-63. When this value is set to 63, it represents that the energy output by the probe is 1mw.

In actual measurement, the probe should work at high frequency as much as possible, because it can better use the average filter of the system to minimize the measurement error. Then, adjust the energy level of the probe to adapt to the measurement frequency, to obtain better measurement results. Generally, there is a direct correspondence between the measur-ement frequency and the energy level, that is, high laser power level is required when working at high frequency, and low laser power level is required when working at low frequency. The correspondence between the measurement frequency and the energy level can be determined by the Signal-to-Noise Ratio (SNR) and total signal quality evaluation indicators given by the probe. The SNR is a parameter that reflects the quality of the interference fringe image. 100% SNR represents the best image quality, and the corresponding measurement accuracy is also the highest.

However, 100% of the SNR value cannot be achieved in actual measurement. Each measurement point in the measurement system corresponds to a corresponding SNR value, and the point with a high SNR value will have a high accuracy. Generally, points less than 50% will be directly filtered out. Total, which is the total amount of light detected by the CCD of the sensor in each measure. Acceptable values that can get accurate results of Total should be between 1200 and 18000. However, it is recommended to set this value range between 2000 and 16000 in actual measurement.

2.2 FPP sensor

FPP is one of many structured light patterns, which is widely used in various high-precision optical three-dimensional measuring equipment [22]. The principle of FPP 3D measurement technology based on digital grating projection is to project a series of sinusoidal grating fringe patterns with different phase shifts to the surface of the object to be measured, and use the camera to collect the deformed grating fringe modulated by the shape of the object surface, so as to calculate the 3D shape data of the object surface to be measured. The principle is shown in Figure 2.

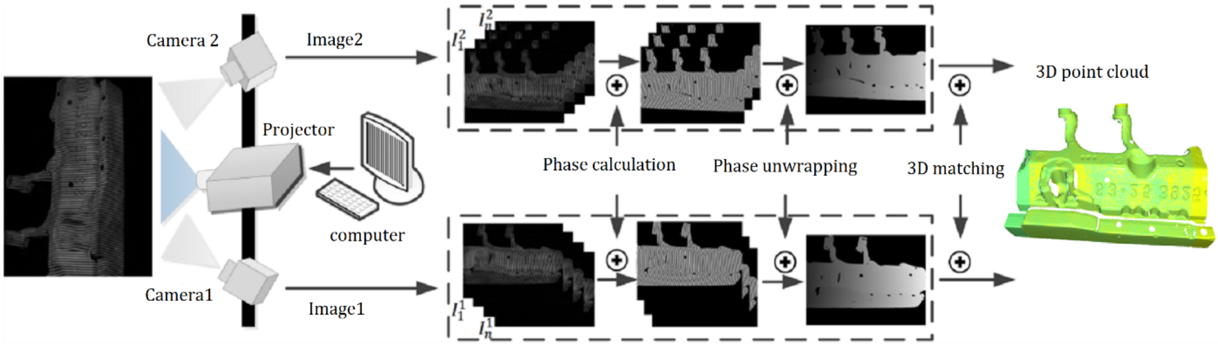

Figure2. Principle of the fringe projection method

As shown in Figure 2, a series of sine grating stripes are throwed onto the measured object. The camera1 and camera2 simultaneously photograph the grating stripes modulated by the shape of the surface of the measured object. The captured grating images can be expressed as

$$I_i(x,y) = A_i(x,y) + B_i(x,y)\cos(\phi(x,y) + \delta_i), i = 1,2,\dots,n, \tag{1}$$

where (x,y) is the pixel coordinate on the captured image, $I_i(x,y)$represents the gray value of the pixel, $A_i(x,y)$ represents the average gray level of raster pattern image, $B_i(x,y)$represents modulated gray level, δ_i is the fixed phase shift, n is the total number of phase shifts, $\phi(x,y)$is the magnitude of the phase shift to be determined. According to formula (1), the $\phi(x,y)$ can be calculated as:

$$\phi(x,y) = -\arctan\left(\frac{\sum_1^n I_i(x,y)\sin(\delta_i)}{\sum_1^n I_i(x,y)\cos(\delta_i)}\right) \tag{2}$$

The range $\phi(x,y)$of calculated by equation (2) is $[-\pi,\pi]$, and its corresponding phase shift image has a discontinuity of 2π. Therefore, phase unwrapping is also needed to obtain a continuous phase-shift image. In this paper, multi-frequency heterodyne technology [23] is used to expand the phase image. After the continuous phase-shift images of the camera1 and camera2 are obtained, respectively, the corresponding pixel points of the same 3D point in the two cameras can be conveniently obtained by using the polar constraints and phase constraints, and finally the 3D coordinates of the point can be computed by using the binocular stereo vision principle.

The FPP sensor used in this article is manufactured by our laboratory, which has a sine pattern projection unit and two cameras. The resolution of the camera in the system is 1920 × 1080 pixels and 60 frames per second acquisition frame rate. When the optical scanning system standard VDI/VDE 2634 [24] is used to test, the accuracy of the sensor can reach 0.02 mm.

2.3 System Configuration

The integrated inspection system comprises an FPP sensor, a CH sensor, and a four-axis precision motion table that has three linear axes and one rotational axis. The specific composition of the developed equipment is depicted in Figure 3. The FPP and CH sensors are mounted on the Z-axis (vertical axis) and move along the Y-directions (horizontal directions). The measured blade is mounted on the rotational part of the platform using a special fixture and moves along the X-axis (depth axis). The parameters of the four-axis motion platform are given in Table 2.

Four coordinate systems are defined for the configuration of the integrated noncontact measuring system, as shown Figure 3.

- The coordinate system of FPP, referred to as the FCS (O_f, X_f, Y_f, Z_f)
- The intrinsic coordinate system of the CH, referred to as the CCS (O_c, X_c, Y_c, Z_c)
- The world coordinate system, referred to as the WCS (O_w, X_w, Y_w, Z_w)

In order to collect the integral three-dimensional data of the blade, the cloud-of-points (CoP) measured by the FPP sensor in the FCS and CH sensor in the CCS should be converted to the same coordinate system (i.e., the WCS).

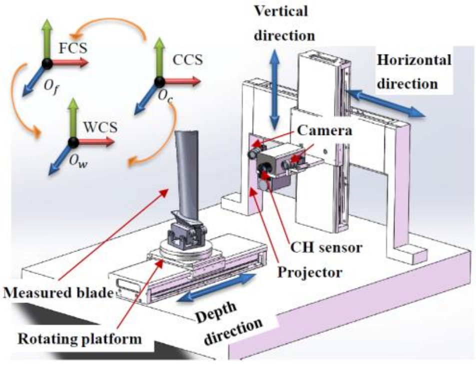

Figure 3: Structure of the integrated inspection system

Table 2. Parameters of the four-axis motion table

Name	**X**	**Y**	**Z**	**Rotary Table (R)**
Measurig range	240mm	200mm	380mm	360°
Velocity	0-60 mm/s	0-60 mm/s	0-60 mm/s	3-15 Rev/min
Axis Misalign	3"/200 mm	3"/150 mm	3"/150 mm	Runout ≤ 0.5μm
Position Accurac	3μm	3μm	3μm	±3 arc sec
Repeatability	< 1.5μm	< 1.5μm	< 1.5μm	< 1.5 arc sec
Carrying	100kg	100kg	100kg	20kg

3. Development of Measurement System

In order to content of precise and efficient size inspection and reverse measurement of the turbine blades, in this paper, a three-dimensional measurement system is developed based on multi-optical sensors. The system hardware includes: four-axis precision motion platform, multi-optical sensors and special fixture. The software uses QT to develop the framework and interface, and uses C++to write relevant algorithms to realize hardware control and human-computer interaction.

3.1 Hardware Platform

The hardware of the developed fusion measurement system mainly includes: four-axis linkage precision motion control system (IMAC400 motion control card, three-axis precision translation guide rail, turntable, servo motor, grating ruler, cast iron platform, PC and electric control cabinet), FPP sensor, CH sensor and special fixture, as shown in Figure 4.

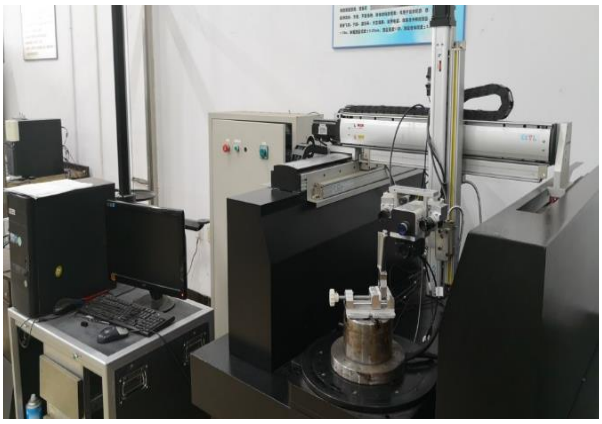

Figure 4: 3D measurement prototype with multi-sensor integrated

The FPP sensor and the CH sensor are fixed on the Z-axis of the four-axis precision motion control platform to perform the scanning of the blade.

Adjust the relative position between the probe and the blade profile through the three linear axes of the motion control system to meet the requirements of each optical sensor for measuring distance. The blade is fixed on the rotary table by a special fixture (anti-collision design), and the pressure surface, suction surface, inlet side and exhaust side of the blade are measured by the rotation of the rotary table. The PC loads the dynamic database through the developed measurement software, connects the control panel of multiple optical sensors and the IMAC400 motion control card, realizes the joint control of motion and data acquisition, and completes the automatic measurement command. The composition of each part is shown in Figure 5.

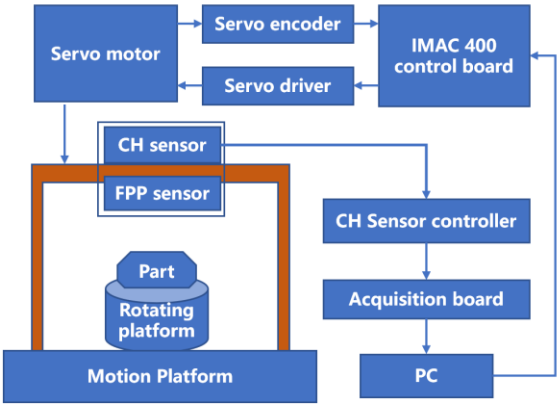

Figure 5: Component relationship of the control system

3.2 Software Program

The software program is an important part of the non-contact fusion blade measurement system. The motion control interaction part is a secondary development based on the SDK development kit of IMAC four-axis motion control card. It calls relevant control functions to realize the precise motion control of three linear axes and one rotary axis servo motor.

The CH sensor reads directly the position feedback information from the grating encoder to obtain the relative position change between the sensor and the measured object.

3.2.1 Development Environment

Qt is a multi-platform C++graphical user interface application framework. It provides application developers with all the functions needed to create a user interface. Qt is completely object-oriented, easy to extend, and allows component programming. Applications developed using Qt can be compiled and run on any supported platform without modifying any source code. It will automatically display the unique graphical interface style of the platform according to the different platforms. Qt is open-source code and provides a free software user protocol, which provides convenient conditions for its wide application in software development on various platforms. Qt provides three authorization methods. The functions and performance of these three authorization methods are the same, only due to the different authorization protocols. LGPL and GPL are released free of charge, while the commercial version requires a licensing fee.

The measurement system software is developed on the Windows operating platform. The measurement software loads the functions in the IMAC400 control card in the form of a dynamic link database, exports and releases the control functions into a writable header file, and adds a statement containing the header file to the application program to realize the call to the library functions.

3.3.2 Interface Design

The measurement system software is the interactive interface between the operating user and the fusion measurement system, as shown in Figure 6. According to the requirements for data acquisition of complex blade surface, the designed software includes five modules: motion control system parameter setting, FPP scanning measurement, CH precision measurement, data processing and 3D display. The position of the measuring point and the number of motion steps are displayed by QT static control, and the default refresh frequency is set. The commands such as automatic measurement command and motion control are implemented through the button control, and the internal function is written to complete the linkage control of the data acquisition process. Window 2 is used to display the measured point cloud data.

频率 1500
能量 50
微调能量 0
信噪比阈值 40
能量阈值 750
轴号 Z
速度 30
位移 -20.00
垂直步距 (标定) 0.20
垂直步数 (标定) 60
水平步距 (标定) 12.00
旋转角度 (标定) 90°
轴中心X (设定) 0.0000
轴中心Y (设定) 0.0000
垂直步距 (配准) 0.10
垂直步数 (配准) 200
垂直长度 (配准)
水平步距 (配准) 15.00
垂直步距 (规划) 0.50
水平步距 (规划) 1.00
垂直步距 (搜索) 0.50
垂直步数 (搜索) 0
水平步距 (搜索) 2.00

Figure 6: Software interface integrating measurement system

3.3.3 Analysis of Software Functions Module

From the perspective of control parameter setting, scanning function realization, data processing and fusion of the whole blade fusion measurement system, the system software includes the following five functional modules:

(1) Motion control module. This module is mainly used to open the board, initialize the board and set the motion parameters. Because the measurement software has many functions to realize, in order to optimize the user's operating experience and reduce the keyboard input time, a large number of parameters are set in the way of program embedding. During the initialization process, some default values of parameters are given that have little impact on the measurement. The parameter setting module is mainly used to manually set the motion axis number, speed, displacement, acceleration, deceleration and smoothing time.

(2) FPP module. It is mainly used to quickly scan the measured blade and obtain relatively complete 3D point cloud data of the blade surface (due to the limitation of measurement principle and sensor resolution, the position of the inlet and exhaust side of the blade cannot generally obtain enough measurement data points). This module is mainly composed of camera parameter setting, camera calibration, noise deletion and rough data registration.

(3) CH module. It is mainly used for the functions of opening the CH probe, manually moving the probe, opening the continuous measurement mode of the probe and ending the measurement. According to the design requirements, the software realizes automatic measurement. At the same time, in order to content of diversity detection, an independent control program for motion setting of the CH probe is developed. During the measured process, the laser probe needs to be adjusted to meet the requirements of measuring the depth of field. Therefore, the motion control parameter setting window is added, and the motion control function of the motion control module is directly called to realize independent jog and continuous control of the servo motor. Jog motion can accurately control the movement distance of each axis, while continuous motion can move the specified distance at a certain speed. It is mainly composed of CH probe parameter setting, measurement path planning, and accurate registration of coordinate system.

(4) Data processing module. It is mainly used for denoising, triangulation, global coordinate system registration and data fusion of multi-optical sensor data.

(5) 3D display module. this part is mainly used to display the 3D digital model of the blade, scan the measurement CoP, data rough registration results, precision registration optimization results, measurement path planning results, etc. In order to facilitate the operator's observation and interaction, and measure whether the obtained blade profile point cloud data is complete, this display module is compiled.

4. Measurement Experiment and Result

In order to further prove the effectiveness of the developed measuring system, a certain type of blade with a high reflective surface was measured.

4.1 Measurement Process

The measurement flow of the blade special fusion measurement system developed in this paper is as follows:

Step1. Clamp the blade on the special anti-collision fixture.

Step2. Use the FPP sensor to scan and measure the blade quickly, obtain the CoP of the blade profile as complete as possible. Then, solve the normal vector of the point cloud and process the noise. Finally, estimate the main direction and secondary direction of the measured blade.

Step3. Perform rough coordinate system registration between the FPP measurement point cloud and the blade CAD model, and transform the coordinate system according to the calibration results of the FPP and CH coordinate systems.

Step4. Use CH to measure the missing part of blade data and the inlet and exhaust edges. Then, sample some points on the point cloud of FPP that can completely represent the surface. Those points are then used to guide the sampling of CH.

Step5. Perform data fusion using Gaussian process model [25] to obtain the best 3D measurement results.

4.2 High Reflectivity Blade Measurement

According to the above measurement process, firstly, several predefined positions of the blade are measured with the FPP sensor. Figure 7 (a) shows the measurement site of the reflective blade; Figure 7 (b) (c) shows the CoP of pressure and suction surface, respectively, measured by the FPP sensor. Obviously, there are many empty areas with the measured CoP data due to the high reflection of the blade surface, especially at the inlet and exhaust edge of the blade, and almost no measurement points have been obtained. Then, use CH to measure the missing part caused by high reflection and the position of the intake and exhaust edges, and the profiles are sampled and measured. The total measurement time of the two methods is 12.5 minutes. The two methods obtain 283299 measuring points in total. After the calibration of the global coordinate system, the measurement data of the two sensors are converted to the same coordinate system, and the fusion results are shown in Figure 8.

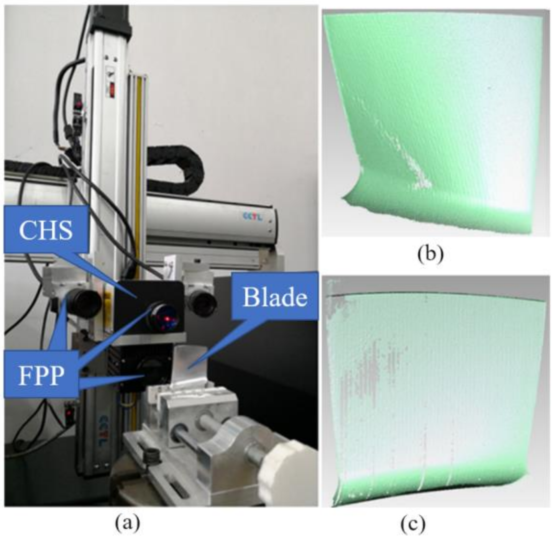

Figure 7: High reflectivity blade measured by the development device: (a)working scene, (b) pressure surface measurement by PFF, and (c) suction surface measurement by FPP.

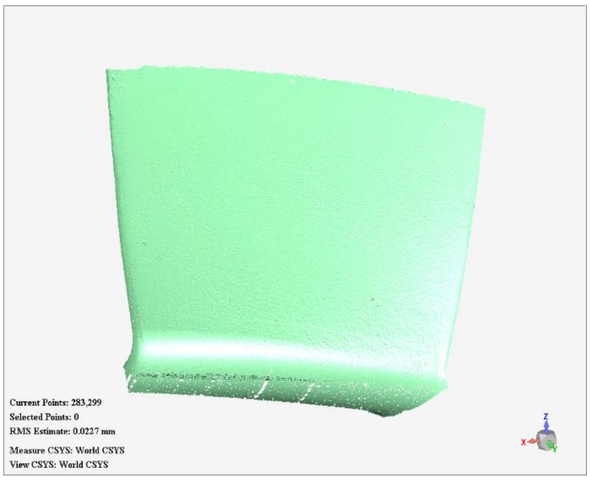

Figure 8: the fusion result of FPP and CH

High-precision full-size measurement of the free-form surface is a time-consuming inspection process for CMM. Generally, the blade first designs the section line, and then stretches and lofts to form a surface. At present, the blade profile parameters (such as chord length, chord angle, maximum thickness, inlet and exhaust edge radius, etc.) and profile parameters (such as blade shape tolerance, blade profile thickness tolerance, inclination tolerance, twist tolerance and bending tolerance, etc.) are mainly calculated by detecting the blade section line. Profile detection is a common method for blade enterprises, but it cannot effectively reflect the condition between blade profiles. As shown in Figure 9, the difference between the two profiles of the blade is caused by flutter and other reasons during blade processing.

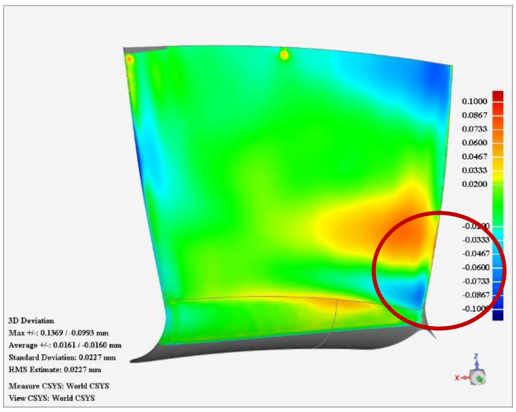

Figure 9: 3D color map of the fusion result

Using a single sensor cannot achieve full-size measurement with both measurement efficiency and accuracy. Using the advantages of various sensors to achieve complementary fusion measurement will become an effective measurement method. The data fusion method proposed in this paper fuses the measured data, and the result comparison analysis is shown in Figure 9. The maximum positive deviation after fusion is 0.1369mm, the maximum negative deviation is 0.0993mm, and the standard deviation is 0.0227mm. The accuracy after fusion has been improved greatly compared with that before fusion.

5. Conclusions

This paper first introduces the principle of the FPP sensor and the CH sensor and their advantages and disadvantages. On the basis of making full use of the advantages of high efficiency of the FPP sensor and high accuracy of the CH sensor, combined with the multi-axis motion control system, the integrated 3D measurement hardware platform is developed. Then, according to the measurement characteristics of the system, the software module is developed and the function of the module is analysed in detail. Based on the development of software and hardware, the 3D measurement system of the turbine blade is developed. Through the full-size measurement of a high-reflectivity blade and the comparison and analysis of the measurement results with the CMM, the measurement capability and effectiveness of the developed system are verified. The measuring system developed in this paper can realize a variety of flexible applications, and has broad application prospects and promotion space.

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