Innovative optical scanning technique and device for three-dimensional full-scale measurement of wind-turbine blades

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Abstract. A full-scale three-dimensional profile measurement system with an innovative optical setup for measuring the geometric shape of large wind-turbine blades in high accuracy is developed. A normal full-scale wind blade geometry measurement system can be very expensive. The presented system is low cost, but it can yield a high accuracy for geometric dimensions by error compensation from its measured data. It consists of a low cost long linear stage driven by a direct current motor with linear scale feedback for position and velocity control, and two line-scan optical heads mounted on opposite sides. The line image of the sectional shape profile can be captured by two charge-coupled devices. By scanning the optical head throughout the full length of the blade, the image of the whole profile can be collected. The shape parameters of the wind-turbine blades can thus be determined. A special effort has been employed to improve the straightness and positioning accuracy of the linear stage by error compensation. With system calibration of the stage and the cameras, experimental results show high accuracy of the developed system. This low-cost optical system is expected to measure any full-scale wind blade profile up to several meters in length. © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.OE.53.12.122411]

Keywords: innovative optical system; wind-turbine blade; three-dimensional profile measurement; scanning mechanism; triangulation method.

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1 Introduction

In recent years, wind energy technology has become a growing market worldwide. The wind-turbine blade (wind blade) is one of the most important parts of wind-turbine machinery. The characteristic parameters, pressure ratio of the engine and rotating speed of the turbine, are all related to the shape and size of the wind blades. Therefore, the profile measurement of the turbine blade is an essential issue in the blade manufacturing. However, it is difficult to establish an effective but accurate process to measure the profile of a wind blade because of its complicated geometry and very long length. For automated manufacturing of wind blades, the need for an effective and accurate measurement system for these massive structures is urgent.

Current technologies in the blade measurements, such as those for aircraft turbine blades and wind-turbine blades, are largely limited to measurements of a partial or local blade profiles with various optical probes and coordinate measuring machine. 1–5 For example, measuring the blade tip clearance by single-point optical sensors, 1,2 measuring small blades’ profiles with a laser interferometer, triangulation probe, three-dimensional (3-D) laser scanner, and coordinate measurement machine. 3,6 In fact, none of these can provide a complete solution for full-scale large wind blade profile measurements.

A structured light image scanning system for 3-D measurements is often used in industry for reverse engineering. Its main advantages are that it is noncontact, fast, and has a low cost. It can be used in a variety of industries. 7–10 The technique of reverse engineering mostly adopts the triangulation principle. 11–17 A structured laser pattern is projected onto the surface from the normal direction and an image sensor at a specific angle to the surface captures the deformed image of the pattern. Digitizing and fitting the image cloud data, the profile can be reconstructed with a surface fitting technique. The structured pattern can be a point, a line, or an area. The point measurement is too slow if cloud data are to be collected, while the area pattern suffers from lens distortion and low resolution of the charge-coupled device (CCD). In order to achieve a fast and accurate scan on a large surface, a linear stage carrying the probe head, which scans the line pattern across the surface, is the suitable solution if the camera is precisely calibrated. 14,15

In this paper, a full-scale 3-D profile measurement system for large wind blades is presented. The base of this system is a long linear stage driven by a direct current (DC) motor with linear scale feedback. The motion is controlled with a proportional-integral-derivative (PID) algorithm. The long displacement is calibrated by a high precision laser Doppler displacement meter (LDDM). 16 so that the positioning error is compensated. Two sets of laser-camera triangulation heads are mounted on the stage opposite so that both sides of the profile can be simultaneously gained. The camera image is calibrated using a template with the coordinate transformation method. 14 The innovative idea of the developed system is to adopt a very cheap sliding gate mechanism as the linear stage. Based on the concept of “precision machining without precise machinery” proposed by Wu and Ni, 17 the poor
straightness of the linear stage could be adjusted very well, assisted by a laser straightness measuring system during installation. Experimental results of this low cost system show that both the accuracy and the measuring time meet the requirements.

2 Measurement System

2.1 System Configuration

The principle of the developed large scanning machine is illustrated in Fig. 1. A rail at least 2-m long with a carrier driven by the brushless DC motor is required. A linear scale is attached to one side of the rail as the position feedback sensor. On the top of the carrier, a laser-camera triangulation optical head is mounted at each side of the rail. The measured wind blade is horizontally placed on the top and in line with the rail. The laser projects a line pattern onto the blade surface, the distorted line image is related to the profile variation, and can be captured by the CCD camera module setup conforming to the principle of triangulation. Both sides of the sectional shape of the blade can be measured simultaneously. When moving the carrier to different positions, the sectional shape can be scanned by the two optical heads simultaneously. Cumulating all measured lines, the full-scale surface profile can be obtained by surface fitting process. Here, a B-spline method is used. To ensure the accuracy of the measured result, the linear stage and the cameras have to be calibrated. The systematic errors thus can be compensated by software for the enhancement of measurement accuracy. Details of the calibration will be explained in Sec. 4.

2.2 Triangulation Principle

Triangulation measurement is one of the popular measurement techniques. It has the advantages of being a fast computation with easy operation. The 3-D view of a triangulation measurement is shown in Fig. 2(a). Its projection on the XZ-plane with one camera is shown in Fig. 2(b). A is the emitted point of the laser, \( P(x, z) \) is a projected point of \( P(x, y, z) \) on the XZ-plane in the world coordinate \( (X, Y, Z) \), and \( P'(u) \) is its projected focused point along the \( u \)-direction in the image plane \( (U, V) \). According to geometrical optics and similar triangles, the coordinates of point \( P(x, y, z) \) can be calculated by

\[
\frac{f}{u} = \frac{z}{x} \quad \text{and} \quad \frac{b + x}{z} = \cot \theta, \tag{1}
\]

where \( f \) is the focal length, \( \theta \) is the angle between the \( X \)-axis and the light direction on the XZ-plane, and \( b \) is the distance between the light source \( A \) and the optical center \( O \) of the camera lens.

From Eqs. (1), we can get

\[
x = \frac{bu}{f \cot \theta - u} \quad \text{and} \quad z = \frac{bf}{f \cot \theta - u}. \tag{2}
\]

Similarly, using the triangulation relationship on the YZ-plane we can obtain

\[
y = \frac{z}{y}. \tag{3}
\]

Substituting \( z \) from Eq. (2) into Eq. (3), we get

\[
y = \frac{bv}{f \cot \theta - u}. \tag{4}
\]

Therefore, the coordinate of point \( P(x, y, z) \) can be obtained from the measured data of \( (u, v) \) and the fixed parameters \( (f, b, \theta) \) as

\[
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
= \frac{b}{f \cot \theta - u}
\begin{bmatrix}
u \\
v \\
v
\end{bmatrix}. \tag{5}
\]
kits of optical heads, and the computer, as shown in Fig. 3. The stage includes a platform and a carriage which can be moved by the driver. The driver includes a motor, a reducer, a roller, and a motor drive. The linear scale detects the displacement of the stage. The optical kit includes an optical head and a mounting frame. The computer is the core module, which includes PID control and image processing software. The details are described in the following sections.

### 3.1 Long Linear Stage

The traveling distance of the linear stage should be longer than the length of the wind blade. In this study, the measured blade is about 2-m long. Such a long stage has to be specially ordered from a local company. Instead of the expensive long linear stage normally used in the measuring machine, we chose an exceptionally low-cost linear motion mechanism such as is used by many factories for sliding gates. This linear stage is constructed with a long rail of a length of 2.5 m. On one side of the rail, there is a heavy duty roller driven by the brushless DC motor through the motor driver and gearbox in order to reduce the speed. A carriage, carrying the motor gearbox and the roller, can move along the rail under speed control. Note that the cost of a nominal long precision linear stage is nearly 15 times more than that used in our measuring mechanism. On one side of this low-cost rail, we attached a linear tape scale made by RENISHAW Co. (Gloucestershire, United Kingdom) as the displacement sensor for position feedback control. With the developed PID controller, the displacement and velocity of the carriage can be controlled.

Based on the concept of precision machining without precise machinery, with a proper measurement strategy the machine accuracy can be improved significantly by error compensation with a low cost. It is known that such a low-cost long linear stage cannot provide good straightness motion because the rail’s vertical deformation (sag) is unavoidable. During installation, the initial maximum sag was first adjusted to around 12 mm with an electronic level. Then, using a precision laser straightness measurement system to check the straightness of the rail at every 150-mm interval and adjusting the ground thread at each interval position, the vertical straightness of the linear stage could be gradually improved. Figure 4 shows the adjusted results of the last three times, in which the maximum error was reduced from around 440 to 250 μm. A significant improvement was achieved. It is noted that the vertical straightness of the stage will cause an up-down shift of the captured line image during scanning. The stored form of straightness can be used to correct such a shift in the image data. Since the form variation of 250 μm is within the allowable tolerance of the wind blade, data correction is not necessary in our system.

### 3.2 Optical Head

The optical head is consisted of one line laser and one CCD, as shown in Fig. 5(a). This module was purchased from a local company. A strong vertical frame was designed to hold the optical head at each side of the rail. The laser line is long enough to cover the entire width of the blade cross section, as shown in Fig. 5(b).

![Fig. 3 Configuration of the measurement system.](image)

![Fig. 4 Straightness error of the linear stage before and after adjustments.](image)
4 System Calibration

4.1 Positional Error Calibration of the Long Linear Stage

The positional accuracy of the long linear stage is essential to the spacing of the scanned lines across the full length. A commercial LDDM, made by Optodyne Co. (California), was adopted for the calibration of positioning error of the long linear stage. Figure 6 shows the calibrated results for the distance between 40 and 170 cm by two times. Although the errors are large, the repeatability is pretty good. Therefore, the software error compensation strategy can be used during the scanning motion. The positional accuracy can be largely reduced from a maximum of 280 \( \mu \)m to less than 20 \( \mu \)m. Together with the straightness error improvement, the accuracy of the measured full-scale profile can be ensured.

4.2 Camera Calibration

In any image measurement system, the camera used has to be calibrated in order to ensure the accuracy of each pixel coordinate. In this work, a standard template of arrayed square patterns was specially made. The accuracy of this template was measured by an optical measurement system (made by 3DFamily Co., New Taipei City, Taiwan). The positional error of each square pattern was ensured within 10 \( \mu \)m. The calibration setup is shown in Fig. 7, in which two cameras were simultaneously calibrated. The image of the template in each camera is shown in Fig. 8. A series of standard image preprocessing steps has been carried out in terms of Gaussian filtering, threshold binarization, line edge detection, and line thinning. The author’s group has already developed the coordinate transformation method to transform the world coordinate to the image coordinate in camera calibration. Details can be found in Ref. 14. This work adopted the same method. In order to check the accuracy of calibration, we randomly selected some square patterns (with known dimensions) and compared them with corresponding calibrated dimensions in each camera image. The results are listed in Table 1. It can be seen that after calibration, the error of the measured patterns by CCD-1 is <0.25 mm on average with a standard deviation 0.081 mm, while for CCD-2 the mean error is <0.29 mm with a standard deviation 0.275 mm. It is noted that the measured blade has large dimensions and the calibrated results are below the tolerance limit for both cameras.

5 Blade Measurement Results

A large wind blade used in the Whisper-500 wind turbine was taken for measurement on the developed large
measuring machine. The velocity of the linear stage was tuned to the best uniform condition with the PID control algorithm. After the full-length scan, collected cloud data by the two CCDs are shown in Fig. 9(a). Figure 9(b) plots the surface model after being processed by the image processing techniques and B-spline line fitting. Figure 10 shows the entire blade profile after B-spline surface fitting. Figure 11 shows the part of the profile in a cross-sectional view from one end of the blade. The smoothness of the wind blade airfoil shape appears to be satisfactory. Hence, the obtained result is acceptable to estimate the wind-turbine efficiency in the domain of wind energy.

6 Discussions and Conclusions

We present the development of a large scanning mechanism for full-scale wind blade profile measurement from design principle to system integration. One of the highlights is its low cost which could be affordable for a university laboratory. Instead of using an expensive precision linear stage, we modified a standard sliding gate mechanism and added a displacement sensor and a PID controller. However, the accuracy of the constructed long linear stage was not good enough for use. Therefore, an error compensation strategy was carried out to improve the straightness accuracy and the positioning accuracy of the stage to the degree of design specification. As a result, the straightness error has been reduced from 155 mm to only 250 μm and the positioning error has been reduced from a maximum of 280 μm to less than 20 μm for the full length of travel. This error compensation strategy is based on the concept of “precision measurement without precise machinery” proposed by Wu and Ni.17 The next highlight of this measuring system is to employ dual optical heads to measure both sides of the blade with a single scan, which could achieve direct and fast 3-D measurement. The measurement accuracy and standard deviation both could be achieved within 0.3 mm after camera calibration. This specification meets the requirement of industrial applications.

A full-scale wind blade has been measured in this developed test bed. By using B-spline line and curve fittings, the surface model of the blade could be generated. So far, we

### Table 1

<table>
<thead>
<tr>
<th>Pattern size</th>
<th>Measured by CCD-1</th>
<th>CCD-1 error</th>
<th>Measured by CCD-2</th>
<th>CCD-2 error</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.52</td>
<td>41.180</td>
<td>−0.34</td>
<td>42.20</td>
<td>0.68</td>
</tr>
<tr>
<td>41.52</td>
<td>41.237</td>
<td>−0.283</td>
<td>41.695</td>
<td>0.175</td>
</tr>
<tr>
<td>41.52</td>
<td>41.321</td>
<td>−0.199</td>
<td>41.670</td>
<td>0.15</td>
</tr>
<tr>
<td>41.52</td>
<td>41.268</td>
<td>−0.252</td>
<td>41.561</td>
<td>0.041</td>
</tr>
<tr>
<td>41.52</td>
<td>41.391</td>
<td>−0.129</td>
<td>41.958</td>
<td>0.438</td>
</tr>
</tbody>
</table>

(Mean error, standard deviation) 
(−0.241, 0.081) (0.289, 0.275)

Fig. 8 Captured images of the CCD-1 and CCD-2.

Fig. 9 Measured wing blade profile: (a) cloud data and (b) after B-spline line fitting.
have not compared our results with data obtained by other measuring systems for these blades because such a large measurement system is rare in the market. Ground vibrations will also affect the measurement accuracy of the full blade. In addition, the captured line image covers only a small window of the image frame. If the calibration could be made while only focused to such a narrow window, the results would be more accurate. Related studies to these issues are in progress.

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References


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