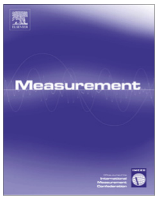
Measurement 79 (2016) 53–65

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement



Offshore wind turbine blades measurement using Coherent Laser Radar

Jeremy Talbot [a], Qing Wang [a,*], Neil Brady [b], Roger Holden [b]

[a] School of Engineering and Computing Sciences, Durham University, DH1 3LE, UK
[b] Nikon Metrology UK Ltd, Staffordshire B77 5ES, UK

ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form 10 October 2015
Accepted 22 October 2015
Available online 30 October 2015

Keywords:
B-spline
Coherent Laser Radar (CLR)
Data alignment
Degrees of Freedom (DoF)
Transformation
Wind turbine blades

ABSTRACT

To maximize aerodynamic efficiency, large-scale offshore wind turbine blades require inspection during the production stage to ensure strict tolerance requirements are met. During production, the blade is fixed at the root, restricting movement in the *Z* direction. *X*, *Y*, *Rx*, *Ry* and *Rz* remain unconstrained causing blade flex due to gravity. This deforms the blade away from the theoretical CAD blade location, causing measurement results that do not accurately represent the blade profile. Measurement error can be minimized using rigorous B-spline data alignment. Such alignment compensates for blade flex by varying the constrained Degrees of Freedom (DoF), and provides manufacturers with confidence in the design process. This paper used Coherent Laser Radar and Spatial Analyzer to establish the optimal constrained DoF variation, giving the most accurate data alignment solution. Of the constraints investigated, the optimal data transformation solution was found with a double B-spline alignment method, whilst constraining movement in *Y*, *Z* and *Ry*.

1. Introduction

Changing climate and increasing awareness of environmental issues in recent years has resulted in a huge increase in the use of low-carbon technologies, particularly wind energy. The contribution of electricity generation from renewable energy has increased from 2.6% in 2000 to 11.5% in 2012 [1] (a target of 15% is set for 2020). Of this renewable energy, 47% is produced by wind power (29% onshore and 18% offshore). This is expected to increase further still.

To produce a large quantity of energy (usually between 1.5 and 4 MW), wind turbines must be extremely large and are therefore subject to strong wind loads. To ensure blades can survive these high wind loads whilst remaining lightweight, they are manufactured with an internal frame supporting an outer shell made from reinforced plastics [2,3].

To maximize aerodynamic efficiency, turbine blades must satisfy extremely tight tolerances and are therefore inspected during manufacture. However, inspection shows a divergence from the theoretical blade design due to shrinkage of the reinforced plastic during manufacture and blade flex under its own weight. Hence, minimizing the three-dimensional (3-D) measurement error during blade inspection is imperative. It provides manufacturers with confidence in the design process; highlighting areas of the blade that deviate away from the CAD model allows the production of more aerodynamically efficient blades.

If flexible, deformation of a turbine blade (or any structure) can consist of up to six Degrees of Freedom (DoF): translational (*X*, *Y* and *Z*), and rotational (*Rx*, *Ry* and *Rz*) directions. Fig. 1 shows a typical large-scale wind turbine blade with a reference coordinate frame showing the translational *X*, *Y* and *Z* directions.

---

* Corresponding author. Tel.: +44 191 334 2381; fax: +44 191 3342408.
E-mail addresses: jtalbot.gcap@gmail.com (J. Talbot), qing.wang@durham.ac.uk (Q. Wang), neil.brady@nikon.com (N. Brady), roger.holden@nikon.com (R. Holden).

http://dx.doi.org/10.1016/j.measurement.2015.10.030
0263-2241/© 2015 Published by Elsevier Ltd.

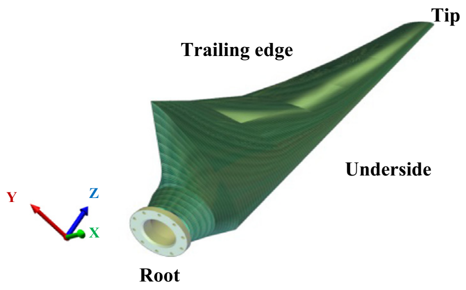


Fig. 1. A typical wind turbine blade. (Blade image by M.A. Homel [4].)

The blade is also free to rotate about the *X*, *Y* and *Z* axes, relating to *Rx*, *Ry* and *Rz* rotational directions.

The inspection of turbine blades compares the measured blade data to nominal point groups on a computer-aided design (CAD) model using data alignment techniques. These techniques transform the measured data using different constrained DoF variations to account for blade flex. The measurement error is minimized by establishing the most accurate DoF constrained data alignment variation.

There are a number of software packages available that can provide a platform for such data alignment including Spatial Analyzer (SA) which was used in this investigation.

Nikon have recently developed a method [5] for inspecting turbine blades using CLR; it is currently in use by Vestas Winds Systems A/S. The method divides a blade into sections using multiple scanner locations to measure the entire blade (six locations are needed for a 60 m blade). The blade is clamped at the root, positioned horizontally with the trailing edge directed upward and supported on a 'tray' half way along the length of the blade. It can be assumed clamping the blade at the root in this manner restricts any movement in the *Z* direction, allowing inspection through five DoF.

An advantage of this method is CLR's unique ability to precisely measure with retroreflective mirrors. Using dedicated mirrors expands the range of sight, enabling the measurement of difficult-to-access areas such as the underside of the blade, allowing accurate inspection of the entire blade.

The data alignment technique currently used by Nikon implements *Z*, *Rx*, and *Ry* constraints, allowing movement in the *X*, *Y* and *Rz* directions. As this method has only recently been developed, very little experimental evaluation has been carried out; DoF constraint variations have been chosen using trial and error. This is especially true of the use of mirrors in CLR. The method therefore requires validation before it becomes common practice industrially.

This research investigates the Nikon inspection method and continues the work that demonstrated a data alignment solution based on a 'D-shaped', semi-circular blade design [6]. This research uses a similar method to that in [6] on a more complex, realistic blade profile which necessitates the use of mirrors.

Measurement error is minimized by evaluating each DoF constraint variation to determine the optimal data alignment solution. The results will propose the most accurate and time-efficient data alignment measurement solution for the large-scale metrology of wind turbine blades using CLR technology. Additionally, effects of using a mirror on measurement accuracy are investigated.

2. Theory

2.1. Coherent Laser Radar technology

There are a number of metrology techniques available today [7] capable of measuring structures on a large-scale. The high accuracy of Coherent Laser Radar (CLR) along with its non-contact technology, application to large-scale structures, speed and portability are all key features shown in Fig. 2 which make CLR the optimal metrology technique for turbine blade inspection.

Contact metrology typically uses touch probes in contact with a surface to measure 3-D coordinates. Historically, contact devices have been able to measure surfaces to a higher accuracy than that of non-contact devices. Nikon's CMM contact devices can measure a 3-D point to a volumetric accuracy of 1.8 μm [9]. More recently, non-contact technology has advanced and is now capable of measuring to a high accuracy [10].

There are several disadvantages to using touch probes for contact methods. They are slow, require an operator, are difficult to manipulate and must be in contact with the surface which could potentially deform the measurement surface and requires the calculation of touch probe radius offsets [11]. Using touch probes for large-scale applications would therefore be extremely time-consuming; CLR can achieve a 90% inspection cycle time reduction compared with alternative contact methods [12].

Due to the large size of turbine blades, multiple CLR scanner locations are needed to inspect a complete blade. However, CLR scanners are portable and the method is fast. The CLR equipment used in this piece of research is Nikon's FM CLR Scanner (LR 200) [13], which is capable of inspecting up to 2000 points per second with a range of 50 m.

The scanner works by emitting a linear infrared laser beam onto the measurement surface and recapturing a portion of the reflected light. The laser signal's strength and ability to accurately focus at any distance from the scanner is maximized with an adjustable, large-aperture fixing [8]. Heterodyne detection [14] of the reflected beam mixed coherently with a controlled reference signal of calibrated wavelength (Fig. 3) can precisely measure the change in frequency (Δf) and the change in time (Δt) of the waveform.

The absolute range is determined using frequency modulation as shown in Eq. (1) [8].

$$\text{Range} = \frac{\Delta f}{0.667} \quad (\mu, \text{microns}) \tag{1}$$

Calculating the measurement points using frequency modulation produces a more accurate reading than if using light modulation shown in Eq. (2) [8]. At a distance of 2 m