Continuous Line Laser Thermography for Damage Imaging of Rotating Wind Turbine Blades

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Abstract

This paper proposes a continuous line laser thermography technique for damage visualization of wind turbine blades under rotating condition. Although a number of non-destructive testing techniques have been proposed for damage inspection of wind turbine blades under stationary condition, a few prior studies on the operating blade monitoring have been reported due to technical challenges associated with actual implementation issues. The proposed continuous line laser thermography technique is able to inspect wind turbine blades with fully noncontact mechanism, no couplant requirement, data acquisition without spatial scanning mechanism and intuitive data interpretation. First, thermal waves are generated by a continuous line laser beam targeted onto the rotating wind turbine blades, and the corresponding thermal responses are simultaneously measured by an infrared camera. Then, a new pixel tracking and statistical pattern recognition algorithms are developed and applied to the measured thermal images in the time domain so that only damage features can be extracted even under the rotating condition of wind turbine blades. The performance of the proposed continuous line laser thermography technique is verified through scaled wind turbine model tests under varying rotating speed.

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Keywords: Continuous line laser thermography; Rotating wind turbine blade; Non-destructive testing; Damage visualization;

1. Introduction

The wind turbine blades are mainly composed of the composite materials due to its unique characteristics such as high strength, light weight and corrosion resistance. Since the composite materials are, however, fabricated by

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laminating multiple layers, they are often susceptible to temperature, humidity, external impacts and especially repeated cyclic loadings [1, 2]. Such susceptibility may cause critical damage inside the blades themselves. The main technical challenge for inspection of the internal damage is that one cannot recognize the damage on the surface by naked eyes. Recently, since the wind turbine blades are getting larger to maximize the wind turbine’s energy output, the collapse of such large wind turbine blades may lead to more serious safety accidents [1]. For example, nowadays, to generate 3000 kW, 50 m wind turbine blade has been typically used. To prevent these accidents, in-situ wind turbine blade monitoring methods are strongly required.

The most widely used in-situ wind turbine blade monitoring technique, especially for the rotating condition, is vibration analysis technique [3, 4]. By measuring the various vibrating frequencies of the wind turbine blades, the physical conditions of material such as damage occurrence and growth can be estimated. Then, strain gauges have been applied for in-situ monitoring with measuring the local strain of the wind turbine blades. However, they are often vulnerable to the long term use [5, 6], and insensitive to internal damage. Although optical fiber sensors have been used as an alternative thanks to their long-term durability [7], the internal damage is still difficult to be detected. More recently, the sensor based ultrasonic technique has been developed for in-situ wind turbine blade monitoring on the basis of its superior sensitivity to the local and internal damage even though its size is small [8]. However, the sensor-based ultrasonic technique often requires complex data processing and low reliability, meaning that it can cause the false alarm due to the vulnerability to the operation noises [9, 10]. Furthermore, permanently installed sensors and wirings will be deteriorated over time, and their maintenance and replacement might be challenging when it comes to embedded sensors. To address these problems, a laser based ultrasonic technique has been developed as non-contact approach [11]. Although it has advantages of the high detectability for internal damage and intuitive damage interpretation, long data acquisition time and low signal-to-noise ratio disturb its field application.

In this paper, a fully non-contact continuous line laser thermography system is proposed for in-situ wind turbine blade monitoring. In addition, the damage imaging algorithm is newly proposed to instantaneously visualize only damage even under operating or rotating conditions. The proposed system and algorithm have following advantages: (1) intuitive damage interpretation by reconstructing the multiple dynamic images to a single static image using coordinate transformation, (2) fully non-contact and automated damage imaging, (3) simultaneous detection of surface damage as well as subsurface one, and (4) no restriction of the field of view in infrared (IR) camera. The performance of the proposed system and algorithm is experimentally verified using a CFRP wind turbine blade specimens in the rotating condition.

This paper is organized as follows. Section 2 describes the continuous line laser thermography system including the hardware configuration and the working principles. Section 3 proposes the damage imaging algorithm for a rotating wind turbine blades, and the experimental validation is shown in the Section 4. Finally, this paper concludes with a summary and discussion in Section 5.

Fig. 1. Schematic diagram of the continuous line laser thermography system.
2. Continuous line laser thermography system

This section introduces the hardware configuration and the working principle of the proposed continuous line laser thermography system. Fig. 1 shows the schematic diagram of a continuous line laser thermography system. The continuous line laser thermography system mainly consists of control, heating and measuring units. The heating unit consists of a laser driver, a continuous (CW) laser, and a cylindrical lens for thermal wave generation on the rotating wind turbine blades consisted of blade I, blade II, and blade III as shown in Fig. 1. The measuring unit is composed of the IR camera, and records the thermal wave propagation on the rotating wind turbine blades. The heating and measuring units are controlled by the control computer in the control unit.

The working principle of the continuous line laser thermography system is as follows. First, the control computer sends out the control signal to the laser driver and the IR camera. Then the laser driver sends out a current signal to the CW laser, and the CW laser emits the point laser beam. Here, the intensity of the point laser beam needs to set properly considering the thermal properties of the rotating wind turbine blades. The shape of the point laser beam is modified to the line laser beam by passing through the cylindrical lens. The line laser beam generates thermal waves onto the surface of the rotating wind turbine blades. According to the surface and subsurface conditions of the rotating wind turbine blades, the thermal wave propagating phenomena are also changed. Typically, the surface and subsurface conditions of the rotating wind turbine blades are abruptly changed nearby the boundary of the damage area, thus the thermal wave propagating phenomena is also abruptly changed at the boundary of the damage area [12]. The IR camera captures the thermal wave propagating phenomena at the rotating wind turbine blades in the time domain as the IR images. The captured IR images are transmitted and stored in the control computer. Finally, the IR images are processed by the damage imaging algorithm and the only damage area is extracted and expressed in the final image.

3. Damage imaging algorithm for a rotating wind turbine blade

The damage imaging algorithm is developed to visualize the damage components on the rotating wind turbine blades. Fig. 2 shows the overview of the proposed processing algorithm. The damage imaging algorithm follows the two major steps: (1) image reconstruction using a coordinate transformation and (2) damage extraction using a statistical pattern recognition. Step (1) reconstructs the multiple $t^{th}$ IR images ($I_t$) to the single reconstruction image ($R$). Then, Step (2) extracts the damage area and constructs final image ($F$) from the image processing algorithm based on the statistical pattern recognition. The detailed procedures are described below.

![Fig. 2. Overview of the proposed damage imaging algorithm.](image-url)
(1) Image reconstruction using coordinate transformation

\[ I_t \] contains the thermal wave induced by the line laser beam onto the rotating wind turbine blades. \( I_t \) shows the thermal waves on the wind turbine blades in the rotating condition within the limited spatial range. However, based on the image reconstruction process, the thermal waves on the whole wind turbine blades can be displayed in the single image in the static condition as \( R \). To reconstruct \( I_t \) in the time domain into the single image as \( R \), the coordinate transformation is performed based on Equations (1).

\[
R_i(x^*, y^*, t^*) = \begin{bmatrix}
0 & 0 & 1 \\
0 & 1 & 0 \\
1 & 0 & 0
\end{bmatrix} I_i(x, y, t)
\]

where \( R_{it} \) is the \( i \)th reconstruction image, and \( x^*, y^*, \) and \( t^* \) is the transformed coordinates from \( I_t \). Here, \( t^* \) is set as the middle point of the width of \( I_t \) \( (w_t) \) and \( R_{wL/2} \) is defined as \( R \).

(2) Damage extraction using statistical pattern recognition

Once \( R \) is constructed, each blade in \( R \) can be separated. Then, the further image processing algorithm is conducted for the damage extraction. First, the thermal wave generated from the line laser beam on \( R \) is eliminated with the remaining the abnormal thermal responses after estimating the normal thermal responses from reference image (Ref) according to Equations (2) and (3), and the abnormal image (A) is constructed.

\[
\text{Ref}(l, y^*) = \sum_{x=1}^{n} R(x^*, y^*)
\]

\[
A(x^*, y^*) = R(x^*, y^*) - \text{Ref}(l, y^*)
\]

Next, the abnormal components on \( A \) is highlighted after the averaging filtering with 5 of the mask size according to Equation (4), and the abnormality enhancement image (E) is constructed.

\[
E(x^*_E, y^*_E) = \frac{1}{25} \sum_{x_A=1}^{x_A+1} \sum_{y_A=1}^{y_A+1} A(x^*_A, y^*_A)
\]

where \( x^*_A \) and \( y^*_A \) is the transformed coordinates of \( A \), and \( x^*_E \) and \( y^*_E \) is the transformed coordinates of \( E \). Finally, the noise components in \( E \) is eliminated by the subsequent statistical analysis. The probability density function of the pixel value of \( E \) is estimated by fitting the Weibull distribution only to the non-zero pixel values and a threshold value corresponding to a 99% of cumulative density function is then calculated. Based on the threshold value, the binary image processing is conducted. The values on \( E \) larger than the threshold values are treated as 1, otherwise zero padded as shown in Equation (5).

\[
F(x^*, y^*) = \begin{cases} 
1 & \text{if } E(x^*, y^*) \geq \text{Threshold} \\
0 & \text{Otherwise}
\end{cases}
\]
4. Experimental validation

The proposed continuous line laser thermography system and damage imaging algorithm are validated through the experiment using the specially fabricated rotating wind turbine blades. The wind turbine blades are fabricated by laminating 15 sheets of 3 K carbon prepregs, and the length, width and thickness is around 500 mm, 200 mm and 3 mm, respectively. The wind turbine blades are under the rotating condition with 5.05 rpm and 261.56 mm/s of the tip speed. Note that the typical rotating speed of the wind turbine blades are 5 to 20 rpm [13]. Three wind turbine blades, blade I, blade II, and blade III, composed of the CFRP material are attached on the rotating motor as shown in Fig. 3. Here, the blade I and III are intact ones, and the blade II has 10 mm and 20 mm of internal delaminations under 0.5 mm from the inspection surface as shown in Fig. 4. Note that the internal delaminations are artificially made by inserting the Teflon tape between 3rd and 4th layer of the 3 K carbon prepreg sheets.

4.1. Experimental setup

Fig. 3 shows the experimental setup for the continuous line laser thermography system. In the continuous line laser thermography system, when the control computer sends out the control signal to the laser driver, the CW laser (TMA-
532-15T, TMA) generates a point laser beam with a 532 nm of wavelength and a 4 mm of beam width. The point laser beam pass through the cylindrical lens and the shape of the point laser beam is modified to the line laser beam with a top hat profile. Then, the reflection mirror guides the line laser beam to the surface of the rotating wind turbine blades. Here, the intensity of the line laser beam is empirically set to 111.11 mW/mm² for the rotating wind turbine blade monitoring. The corresponding thermal waves of the wind turbine blades are recorded by the IR camera (A6700SC, FLIR) as the $I_t$. The IR camera acquires $I_t$ with a temperature resolution of 0.02 K, a sampling rate of 50 Hz, a spectral range of 3 µm to 5 µm and a pixel resolution of 500 µm. The IR camera is apart 1000 mm from the target specimen.

4.2. Experimental results

Once $I_t$ is collected from the continuous line laser thermography system, $R$, $A$, $E$ and $F$ are processed using the proposed damage imaging algorithm. Figs. 5 and 6 show the processed images from the inspection area I and II, respectively, described in Fig. 4. First, $R$ is constructed using the multiple $I_t$'s in the time domain through the image reconstruction algorithm based on the Equations (1) and (2), and shows the thermal responses in the static condition from each blade. Then, $A$ is constructed by eliminating the laser induced temperature at the sound conditions using Equations (3) and (4), showing that only abnormal thermal responses are extracted. Next, $E$ is constructed by magnifying the abnormal areas on $A$ using Equation (5). Finally, $F$ is constructed by extracting the damage components with eliminating the noise components using Equation (6), clearly showing that only internal delamination is shown as white colour in only the blade II. The test results reveal that various noise components successfully eliminated, and no positive false alarm is indicated even under rotation condition of the blade.
5. Conclusion

The continuous line laser thermography system and the damage imaging algorithm is newly proposed for internal delamination detection of rotating wind turbine blades. The proposed system and algorithm are successfully verified through the experiment using the specially fabricated rotating wind turbine blades with width 10 mm and 20 mm of internal damage under 0.5 mm form the surface. The proposed system and algorithm enables (1) Fast and in-situ damage imaging with fully non-contact and automated manner on rotating condition, and (2) Long-distance and precise delamination inspection for massive target structure. However, the further studies for improving the inspection speed and estimating the detectable damage depth are necessary for the real-field applications.

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