Optics and Lasers in Engineering 65 (2015) 38–45

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Determination of three-dimensional movement for rotary blades using digital image correlation

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ARTICLE INFO

Article history:
Received 3 February 2014
Received in revised form
21 April 2014
Accepted 29 April 2014
Available online 27 May 2014

Keywords:
High-speed camera
Digital image correlation
Rotary blade
3D motion

ABSTRACT

Non-contact and accurate motion measurement of the rotary objects is crucial in engineering applications. A modified Newton–Raphson algorithm, which is capable of positioning marks with large rotation, has been proposed. A stereo imaging system with a pair of synchronized digital high-speed cameras was developed and achieved full-field displacement measurement based on 3D image correlation photogrammetry for rotary objects. This system has been applied to measuring the 3D motion of a wind turbine blade model. The displacement components of the rotary blade were presented, and the corresponding frequency spectra were investigated. The experimental results demonstrated that the proposed system could measure the 3D motion of rotary blades precisely, and it also provided an alternative potential non-contact diagnosis means for large wind turbine blades.

1. Introduction

Digital image correlation (DIC) technique provides a non-contact, optical method used to measure the surface displacement and strain of an object as it deforms. DIC has been widely used in many fields because of its distinct advantages such as the simple experimental steps, high accuracy and large range of measurements [1–4]. Three dimensional DIC uses two cameras to calculate the in-plane and out-of-plane displacement components based on the principles of photogrammetry [5], and it has been applied in various fields [6–8]. To measure the 3D motion of dynamic rotary objects, high-speed imaging systems and the optical non-contact DIC technique with abilities involving translation and rotation measurement are always desired [9,10]. This provides a great challenge for the conventional the DIC technique as in many cases the correlation algorithms cannot excel if the object deforms with large rotations. For instance, Zhang et al. [11] proposed a search scheme by introducing affine transform and a nested fine search strategy, which can be potentially applied to solving problems in rotation. Zhou et al. [12] also developed a fully automated approach which uses feature matching to deal with large rotation. Zhao et al. [13] also developed an improved population-based intelligent algorithm to deal with the decorrelation caused by rotation. However, these two algorithms require a large amount of computation time in convergence.

In this study, a modified NR algorithm has been proposed to track marks with large rotation angle using a regular rectangular subset. An affordable high-speed, stereo-camera system has been developed to record dynamic sequential images. Sequential images of a model of the rotating wind turbine blade were acquired from high-speed dual-camera system with frame rates up to 500 fps. The 3D motion of the rotating blade with various rotation speeds (Ω) was analyzed based on digital image correlation. The experimental results showed that the working condition of the rotating wind turbine blade could be evaluated by this non-contacting optical method.

2. Materials and methods

2.1. Modified DIC algorithm

As the movement of an object is generally considered as the combination of rotation and translation, the correlation algorithm should be effective for both types of motion, i.e. rigid body rotation and translation. However, most traditional DIC algorithms with the rectangular subset were not robust to object rotation. To solve this problem, a modified correlation algorithm which can detect rotation has been proposed. The correlation algorithm is divided into three steps. In the first step, the search was conducted in

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http://dx.doi.org/10.1016/j.optlaseng.2014.04.020
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integer pixels. And the square subset in the deformed image was rotated θ degrees according to the following equations:

$$x' = x + \Delta x \cos\theta + \Delta y \sin\theta$$
$$y' = y - \Delta x \sin\theta + \Delta y \cos\theta \tag{1}$$

where x', y' are the integer pixel coordinates of the rotated square subset, Δx, Δy are the distances to the subset center in x and y directions, and θ is the rotating angle. A grayscale array is established according to the brightness at the integer positions in the undeformed image and compared with the grayscale arrays in the deformed image using a standard correlation function. An initial value for the rotating angle θ is assumed as θ degrees to start the search process and the integer pixel position (x', y') in the deformed image with the minimum correlation coefficient can be determined. The displacement components (u, v), which are defined as the differences between the coordinates in undeformed and deformed images in x and y directions, and the rotating angle θ of the subset center in the deformed image are used as the initial values for the follow-up subpixel search. In the second step, the Newton–Raphson algorithm is adopted in the iteration. Generally, the deformation of the subset can be described with a shape function with 12 variables $(u, v, u_x, u_y, v_x, v_y, u_{xx}, u_{xy}, u_{yy}, v_{xx}, v_{xy}$ and $v_{yy})$ [14]. Since the high-order deformation components are small within the subset considering rigid body rotation, the components $(u_{xx}, u_{xy}, u_{yy}, v_{xx}, v_{xy}$ and $v_{yy})$ are neglected at the this stage. The rotating components $(u_x, u_y, v_x$ and $v_y)$ can be expressed with the rotating angle as the following equations:

$$u_x = \cos\theta, \quad u_y = \sin\theta$$
$$v_x = -\sin\theta, \quad v_y = \cos\theta \tag{2}$$

As shown in Fig. 1, the coordinates of the deformed subset can be expressed in the following equations:

$$x^* = x_0 + u + \Delta x \cos\theta + \Delta y \sin\theta$$
$$y^* = y_0 + v - \Delta x \sin\theta + \Delta y \cos\theta \tag{3}$$

Denote the grayscale arrays of the undeformed and deformed subsets as $f(x, y)$, $g(x^*, y^*)$. The correlation coefficient can be written as

$$C_{f,g}(\overrightarrow{P}) = 1 - \sum_{j=1}^{2N+1}\left[\frac{f(x,y)-\overline{f}}{\sqrt{\sum_{j=1}^{2N+1}[f(x,y)-\overline{f}]^2}} - \frac{g(x^*,y^*)-\overline{g}}{\sqrt{\sum_{j=1}^{2N+1}[g(x^*,y^*)-\overline{g}]^2}}\right] \tag{4}$$

$$J(\overrightarrow{P}) = \left\{\frac{\partial C}{\partial u}, \frac{\partial C}{\partial v}, \frac{\partial C}{\partial(\theta)}\right\}^T \tag{5}$$

In this equation, the optimal solution $\overrightarrow{P} = (u, v, \theta)^T$ satisfies the correlation coefficient to reach the minimum value. The initial value $\overrightarrow{P}_0 = (u_0, v_0, \theta_0)^T$ was defined by using u_0, v_0 and θ_0 which were resulted from the integer search. Since the extreme value $\overrightarrow{P}$ must be close to the initial value, the relationship between the $\overrightarrow{P}$ and $\overrightarrow{P}_0$ can be described using a Taylor series.

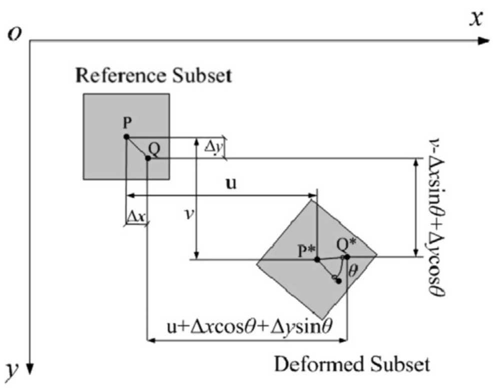

Fig. 1. Subsets before and after rigid body translation and rotation.

$$C_{f,g}(\overrightarrow{P}) = C_{f,g}(\overrightarrow{P}_0) + \nabla C_{f,g}(\overrightarrow{P}_0)(\overrightarrow{P} - \overrightarrow{P}_0) \tag{6}$$

Since $\overrightarrow{P}$ is the extreme position, the first derivative should be equal to zero.

$$\nabla C_{f,g}(\overrightarrow{P}) = \nabla C_{f,g}(\overrightarrow{P}_0) + \nabla\nabla C_{f,g}(\overrightarrow{P}_0)(\overrightarrow{P} - \overrightarrow{P}_0) = 0 \tag{7}$$

Thus, the location $\overrightarrow{P}$ can be derived as

$$\overrightarrow{P} = \overrightarrow{P}_0 - \frac{\nabla C(\overrightarrow{P}_0)}{\nabla\nabla C(\overrightarrow{P}_0)} \tag{8}$$

In the above equation, the first derivatives of the correlation function, which is called the Jacobian matrix was derived as

$$J(\overrightarrow{P}) = \left\{\frac{\partial C}{\partial u}, \frac{\partial C}{\partial v}, \frac{\partial C}{\partial(\theta)}\right\}^T \tag{9}$$

The second derivatives of the correlation function, which is called the Hessian matrix was derived as

$$H(\overrightarrow{P}) = \begin{bmatrix} \frac{\partial^2 C}{\partial u \partial u} & \frac{\partial^2 C}{\partial u \partial v} & \frac{\partial^2 C}{\partial u \partial \theta} \\ \frac{\partial^2 C}{\partial v \partial u} & \frac{\partial^2 C}{\partial v \partial v} & \frac{\partial^2 C}{\partial v \partial \theta} \\ \frac{\partial^2 C}{\partial \theta \partial u} & \frac{\partial^2 C}{\partial \theta \partial v} & \frac{\partial^2 C}{\partial \theta \partial \theta} \end{bmatrix} \tag{10}$$

The movement $(u, v, u_x, u_y, v_x, v_y)$ of the rigid body was measured through the above NR iteration with subpixel precision. The final step was to estimate the rest 6 high-order variables which are related to the deformation and distortion of the subset $(u_{xx}, u_{xy}, u_{yy}, v_{xx}, v_{xy}$ and $v_{yy})$.

2.2. High-speed stereo camera system

A home-designed high-speed dual camera image acquisition system which is composed of two high-speed cameras (Mikrotron EoSens MC1362, Germany), 2 Xcelera image acquisition cards, a signal generator and a computer has been developed. The high-speed camera is able to capture images with spatial resolution of 1280 × 1024 pixels at a rate of 500 fps(frames per second). When the two cameras are working in the external triggering mode, the signal generator can provide periodic pulses synchronizing the cameras to acquire images at given frequency. Since large amount of the image data have to be transferred and stored during acquisition and the storage in hard drive is time-consuming, it is impossible to record the images captured by the 2 cameras in real-time. With the development of computer hardware, the computer dynamic random access memory (RAM) has been enlarged significantly. It provides an instant media to store the huge amount of image data with high speed. In the developed system, the computer has been built with 20 GB memory space, which enables a recording duration of up to 15 s when the dual-camera system is working at 500 fps. Images are then transferred from the memory to the hard drive after sequential images are acquired.

2.3. Experimental procedures

A white model of the wind turbine blade was employed in the experiment. The surface was sprayed with randomly distributed speckles to enhance the contrast. An electric fan was placed in the rear of the wind turbine model to drive the blade to rotate according to its own running speed. The high-speed stereo camera system was placed in front of the rotating blades to acquire dynamic images, as shown in Fig. 2(a). During the experiment, the high-speed stereo camera system was working at 400 f/s. Prior to the measurement, the imaging system was calibrated with a