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Dynamic deformation image de-blurring and image processing for digital imaging correlation measurement

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ABSTRACT

This paper proposes a method for de-blurring of images captured in the dynamic deformation of materials. De-blurring is achieved based on the dynamic-based approach, which is used to estimate the Point Spread Function (PSF) during the camera exposure window. The deconvolution process involving iterative matrix calculations of pixels, is then performed on the GPU to decrease the time cost. Compared to the Gauss method and the Lucy–Richardson method, it has the best result of the image restoration. The proposed method has been evaluated by using the Hopkinson bar loading system. In comparison to the blurry image, the proposed method has successfully restored the image. It is also demonstrated from image processing applications that the de-blurring method can improve the accuracy and the stability of the digital imaging correlation measurement.

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1. Introduction

The identification for the dynamic behavior of materials has traditionally been essential in many engineering applications. Despite the large amount of research activity in this area, testing materials at high strain rates still presents a challenge from the experimental point of view [1]. In particular, the main problem is to measure the strain field of the specimen during deformation at high speed. In order to obtain full-field strain measurements, optical techniques are needed, because strain gages alone only provide pointwise information [2]. The digital image correlation (DIC) method [3] can provide full-field displacement and surface strain field measurement of an object by comparing two digital images of the object before and after deformation. The DIC method has been extensively used in deformation measurements for years due to its advantages of requiring minimal equipment, providing very precise results, and ability to obtain non-contact measurements [4]. The merits of the digital image correlation method recently launch machine vision new opportunities for the use of measurement.

High speed imaging is an important instrument in a wide variety of scientific research applications [5–10]. In the 1990s, the multi-channel framing camera was born which exposure times and optical gain while the beam-splitter with a multitude of intensified CCD cameras [11]. Meanwhile, developments in CMOS sensors [12] have allowed significant advancements in both image quality and speed, with the available cameras capable of recording at rates in excess of thousands of frames per second at full frame [13–15]. However, it exists a trade-off between the spatial resolution and frame rate which are limited by the available output bandwidth. For this trade-off, images at high frame rate are reduced to just a few hundred pixels per frame which is of little use to most applications [16]. The ultra-high-speed camera applied in this research, has a novel sensor architecture named uCMOS. The in-pixel memory depth is 180, the resolution is 924×768 pixels and the sampling frequency in burst model is 5 million frames per second [16]. The short recording time restricts the number of images and decreases the picture quality. They are more than outweighed by the convenience and quantitative analysis obtaining via electronic imaging systems [17].

In the experiment of the dynamic deformation, it is assumed that L is the actual length of the specimen, H is the pixel length in the image, the $\dot{\varepsilon}$ is the strain rate in the experiment and the υ is the frame rate of the camera. The ratio of the pixel length and the actual length is $k=H/L$. The velocity of the specimen deformation is $\mathrm{D} = L\cdot\dot{\varepsilon}$. The blurring region caused by the deformation during one frame captured is $\mathrm{S} = k\cdot D/\nu = H\cdot\dot{\varepsilon}/\nu$. The blurring region caused by rigid motion during one frame captured is $\mathrm{S}_{\mathrm{rigid}} = k\cdot V_{\mathrm{rigid}}/\nu$. The strain rate of the Hopkinson bars is $10^3\sim10^5\ \mathrm{s}^{-1}$. Even though the frame rate of the ultra-high-speed camera has reached 5 M frames per second, the blurring region caused by the deformation in the image is over than 2 pixels, while the strain rate is $10^4\ \mathrm{s}^{-1}$. The blurring region caused by rigid motion can be 10 times more the deformation blur, because of the amplification of the telephoto lens. Hence, it is a significant role to reduce the blur caused by rigid motion and improve the accuracy of the measurement in the identification of the dynamic behavior of materials.

Motion blur takes place due to the relative motion between the camera and object during an exposure window. There are various ap-

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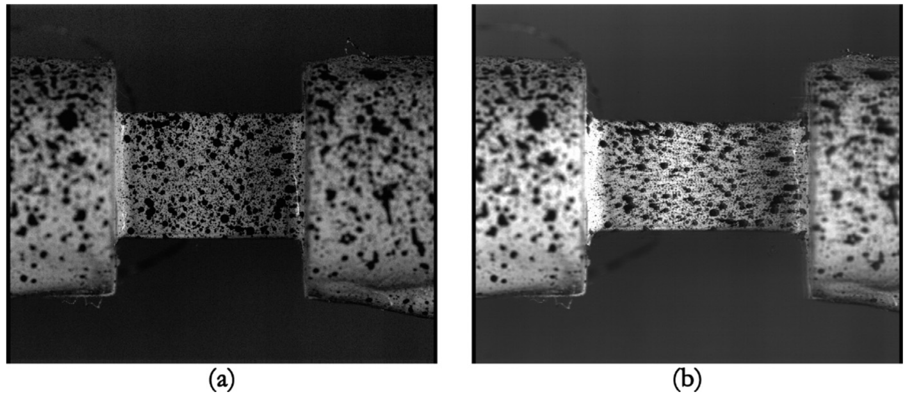

Fig. 1. Blur image in the dynamic deformation: (a) Reference image; (b) Blurry image.

proaches in the computer science field for restoring a latent image from a motion blurred image. The foremost two steps of image de-blurring are Point Spread Function (PSF) estimation and non-blind deconvolution [18]. The PSF, which is otherwise known as a blur kernel, describes the motion during the exposure window. Deconvolution is a recovery process involving the PSF and the blurry image. Many studies analyzed the inherent properties of the image to estimate the PSF by iteratively optimizing a cost function. The further investigations have been conducted on the maximum a posterior (MAP) solution for optimization [19] and the power-law model to estimate the PSF [20,21]. Since the measurement accuracy obtained by DIC is directly related to the quality of the underlying digital images, an important aspect of the measurement process is the image distortion removal procedure [22]. In general, image-based methods for motion blur removal are computationally expensive since the PSF is estimated by iterative and complex methods. The DIC measurement is based on the speckle pattern in the image. The feature reconstruction method is not appropriate to assess the corresponding function. Meanwhile, for the gauss filter, some texture of the target has been vanished in the computation. Accuracy of DIC measurement will be reduced [19,20]. Therefore, the existing methods are not appropriate for the DIC measurement. It is necessary to present a method for the motion blur removal in the dynamical deformation measured by the DIC.

This paper proposes a method for de-blurring of images captured in the dynamic deformation. It is achieved by a dynamic-based approach. The dynamic-based method is used to estimate the Point Spread Function (PSF) during the camera exposure window. The deconvolution process involving the iterative matrix calculations of pixels, is then performed on the GPU to reduce the time cost. The proposed method has been evaluated by using the Hopkinson bar system. In comparison to the blurry image, the proposed method has successfully restored the image. It was demonstrated from image processing applications that the proposed de-blurring method can improve the accuracy and the stability of the digital imaging correlation measurement.

2. De-blurring method

Even though the frame rate of the ultra-high-speed camera has been reached 5 M frames per second, blurred regions in the captured images are unavoidable. As showed in Fig. 1, the blurred area exists because of the dynamic deformation process. Blurred area will influence the accuracy of digital imaging correlation. Among them, the drastic motion of the object will dramatically affect the quality of the image captured by the camera. Therefore, the motion blur, which was produced by the drastic motion during the capture process, can greatly reduce the accuracy and stability of DIC measurement.

Dynamics-based PSF estimation is an open-loop approach without usage of any sensor. The dynamics-based method estimates the PSF in s parallel manner during an exposure window. Then, the deconvolution method is used to restore the latent image [23]. Having accurate system dynamics and input commands given to the system, motion of the system can be estimated if no external disturbances occur. For the dynamics-based approach, the motion system is estimated by the theory of impact dynamics [24–27]. This paper deals with the motion blur caused by fast motion, while the previous studies usually focused on the situation where the exposure time was long due to low ambient light and motion were introduced by shaking of the camera. Meanwhile, the targets of the speckle patterns are considered in this paper. These patterns and processed patterns in previous studies present apparent difference.

In the ultra-high-speed camera acquisition, the state-space representation of a m degree of freedom (DOF) and nth order system can be presented as:

$$\dot{\mathrm{x}}(\mathrm{t}) = \mathrm{Ax}(\mathrm{t}) + \sum_{i=0}^{N-1} [Bu_i(t-t_i)] \quad (1)$$

$$\mathrm{y}(\mathrm{t}) = \mathrm{Cx}(\mathrm{t}) + \sum_{i=0}^{N-1} [Du_i(t-t_i)] \quad (2)$$

$$u_i(t-t_i) = \mathrm{A}_i\delta(t-t_i) \qquad (i \in \ 0, \cdots, N) \quad (3)$$

$$\mathrm{t}_0 = 0, \mathrm{x}(t) \in \mathbb{R}^{n\times 1}, \mathrm{u}(t), y(t) \in \mathbb{R}^{m\times 1}$$
$$A \in \mathbb{R}^{n\times n}, B \in \mathbb{R}^{n\times m}, C \in \mathbb{R}^{m\times n}, D \in \mathbb{R}^{m\times m}$$

where *x(t)* is the state vector, *u(t)* is the input vector, *y(t)* is the output vector, A is the system matrix, B is the input matrix, C is the output matrix, D is the feed through matrix, $\delta(t)$ is the unit impulse function, A_i is the amplitude of ith impulse, and N is the number of inputs given to the system, respectively. The motion of the specimen can be estimated from a set of Eqs. (1)–(3). The PSF represents the motion path with time intensity in the image frame, and can be determined.

In dynamical loading process, the deformation is identified experimentally by the observation of a step response, as shown in Fig. 2. According to the Modern Control System theory, the motion can be represented as a linear second-order system given as [25–27]:

$$\mathrm{G(s)} = \frac{K}{s^2 + 2\zeta\omega_n + \omega_n^2} \quad (4)$$

where K is the residue, ω_n is the natural frequency, and ζ is the damping coefficient, respectively.

The motion of the specimen is described by the strain rate$\dot{\varepsilon}$, the gauge length of the specimenL_0, the damping coefficientζ, the residue K and the Poisson's rate of the specimenσ. Hence, the parameters from (1) to (2) are:

$$\omega_\mathrm{n} = \omega_\mathrm{n}(\dot{\varepsilon}, L_0), A = \begin{bmatrix} 0 & 1 \\ -\omega_\mathrm{n}{}^2 & -2\zeta\omega_\mathrm{n} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \mathrm{K} \end{bmatrix}, C = [\sigma], D = 0$$

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