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Review

Thermal error analysis and compensation for digital image/volume correlation

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ABSTRACT

Digital image/volume correlation (DIC/DVC) rely on the digital images acquired by digital cameras and x-ray CT scanners to extract the motion and deformation of test samples. Regrettably, these imaging devices are unstable optical systems, whose imaging geometry may undergo unavoidable slight and continual changes due to self-heating effect or ambient temperature variations. Changes in imaging geometry lead to both shift and expansion in the recorded 2D or 3D images, and finally manifest as systematic displacement and strain errors in DIC/DVC measurements. Since measurement accuracy is always the most important requirement in various experimental mechanics applications, these thermal-induced errors (referred to as thermal errors) should be given serious consideration in order to achieve high accuracy, reproducible DIC/DVC measurements. In this work, theoretical analyses are first given to understand the origin of thermal errors. Then real experiments are conducted to quantify thermal errors. Three solutions are suggested to mitigate or correct thermal errors. Among these solutions, a reference sample compensation approach is highly recommended because of its easy implementation, high accuracy and *in-situ* error correction capability. Most of the work has appeared in our previously published papers, thus its originality is not claimed. Instead, this paper aims to give a comprehensive overview and more insights of our work on thermal error analysis and compensation for DIC/DVC measurements.

1. Introduction

In the experimental mechanics community, two-dimensional digital image correlation (2D-DIC) [1,2], stereo-digital image correlation (stereo-DIC) [3–6], digital volume correlation (DVC) [7–10] have been widely accepted and commonly used for surface 2D, 3D or internal 3D kinematics fields measurement of solid objects or structures. Practical implementation of DIC/DVC techniques consists two stages: namely digital image acquisition and image correlation analysis. Specifically, in using these image-based deformation measuring techniques, the surface images, image pairs or volume images of a test specimen at different states should first be recorded by a specific imaging device, e.g., a single camera (2D-DIC), synchronized two cameras (stereo-DIC), or a x-ray CT scanner (DVC). The recorded images carry the desired deformation information of the test sample in response to external loadings. By processing these grayscale images, image pairs, or volume images with 2D or 3D registration algorithms and proper numerical differentiation approaches, full-field displacements and strains can be extracted.

In various experimental mechanics applications, measurement accuracy is always the most important requirement. In the last three decades, substantial improvements have been made to 2D subpixel or 3D subvoxel registration algorithms. Currently, by optimizing the robust zero-mean normalized sum-of-squared difference (ZNSSD) correlation criterion using the state-of-the-art inverse compositional Gauss-Newton (IC-GN) algorithm (or 3D IC-GN algorithm) and high-order B-spline interpolation method, the accuracy of subpixel (subvoxel) registration is expected to be higher than 0.005 pixels (voxels) [11–14]. However, considering the complex measurement chain involved in practical DIC/DVC measurements [15] (e.g., speckle pattern [16,17], lighting [18], imaging lens [19–21], CCD sensor [22], camera calibration [23–25], calculation parameters [26–32], correlation algorithm [33–35], etc), it is believed that all these parts should be comprehensively considered to realize high-accuracy measurement of the desired kinematic fields. Regrettably, compared with the long-lasting and plentiful research efforts dedicated to correlation algorithm, there are only a few recent papers that attempt to investigate the effect of imperfect and unstable imaging system on DIC/DVC measurements.

In fact, electronic components inside digital cameras and x-ray tubes in CT scanners generate heat during image acquisition, which is also known as self-heating or warm-up effect. Previous works [36–42] have reported that the temperature of cameras and X-ray tubes in use can increase by several to more than ten Celsius degrees before achieving thermal equilibrium. Aside from the self-heating effect, ambient temperature variations in non-laboratory conditions also change the tempera-

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ture of digital cameras. The increased temperature inside these imaging devices as well as ambient temperature variations will induce tiny thermal movement or position change of camera sensors, optical lenses or x-ray emission points. As a result, these changes alter the image and object distances in 2D/stereo-DIC systems, or the source-to-object and source-to-detector distances in an X-ray CT [38,41]. In other words, the originally assumed or calibrated imaging geometry of these imaging systems is changed. Generally, these slight changes in optical geometry lead to both translation and expansion (or dilatation) in the acquired images, which can be detected by the advanced DIC/DVC algorithms with subpixel/subvoxel registration accuracy and manifested as measurement errors. In this work, the errors in DIC/DVC measurements due to inside or ambient temperature variations are referred to as thermal errors, which can be considered as a kind of systematic error, because magnitudes of these thermal errors are generally in positive correlation with the temperature variations.

As mentioned above, measurement accuracy is always the foremost objective in real DIC/DVC applications. For this reason, we consider that the thermal stability of the imaging system is one of the essential issues that should be given serious consideration. The displacement, especially strain errors, associated with the instability of CCD cameras or x-ray CT tubes should be well understood, quantified and minimized. However, in most publications regarding DIC/DVC, thermal errors associated with unstable imaging geometry have been overlooked. Here we aim to systematically analyze the imaging model used in 2D-DIC, stereo-DIC and DVC, and interpret the underlying mechanism of these thermal errors. Specially designed real experiments were performed to investigate the effect of thermal effects on DIC/DVC measurements. Corresponding solutions that can effectively minimize or correct these errors are discussed and demonstrated. Again it is emphasized here that most of the work has appeared in various papers and its originality is not claimed herein. The primary objective of this paper is to give a comprehensive overview and more insights of our work on thermal error analysis and compensation for DIC/DVC measurements.

2. Thermal error analysis for DIC/DVC

2.1. Imaging models of DIC/DVC

The 2D-DIC using a fixed digital camera is limited to in-plane displacement/strain measurements of planar surfaces. Stereo-DIC using two synchronized cameras can be used to measure shape and surface deformation of complex objects. By processing volume images acquired by a volumetric imaging device (e.g., an x-ray CT scanner), DVC can extract internal displacement/strain fields of oblique solid objects with identifiable microstructures. Considering the fact that basic principles and the corresponding correlation-based image matching algorithms of 2D-DIC, stereo-DIC and DVC have been well documented in various publications, only the imaging models of these techniques are briefly reviewed herein.

When using 2D-DIC, just one camera, whose optical axis should be aligned to be approximately perpendicular to the test planar surface, is needed to capture the surface images of the test specimen before and after loading. The imaging geometry of 2D-DIC can be well explained by the simple pinhole imaging model shown in Fig. 1(a). Specifically, if lens distortion is not considered, the desired physical displacements, U and V, are linearly related to the detected images displacements, u and v, according to $U = Mu$, $V = Mv$. Here the magnification factor M is determined by $M = Z_0/L_0$ with Z_0 being the object distance, L_0 the image distance.

Regular stereo-DIC system comprises two cameras, which synchronously capture the surface images of a test specimen from two different positions and orientations. When using stereo-DIC, stereovision calibration should be implemented first to determine the intrinsic and extrinsic parameters of the two cameras. These calibrated parameters are then used to build a world coordinate system. Based on the calibrated parameters and the disparity maps computed at specified points of interest (POIs) by DIC algorithms, the 3D spatial coordinates, displacements and strains at these points can be retrieved.

In various DVC applications, X-ray CT scanners are undoubtedly most commonly used due to its wide applicability and easy accessibility. An X-ray scanner generally comprises three main components: an x-ray source, a translation/rotation stage, and an X-ray detector [10]. As shown in Fig. 1(c), the magnification of an x-ray CT is therefore determined by the source-object distance d_0 and source-sensor distance D_0.

It should be noted that, in routine use of DIC/DVC techniques, it is implicitly assumed that the imaging geometry of all these systems are stationary without any change during the whole measurement period. However, this assumption is not always true in real tests. Particularly, it was found that electronic components in digital cameras or x-ray tubes inside CT scanners generate heat after powering up, and then raise temperature inside these imaging devices. Before achieving thermal equilibrium, slight thermal movements may occur to the camera sensors, optical lens or x-ray tubes, thus altering the original imaging geometries. Aside from the self-heating effect, ambient temperature variations in outdoor conditions have the same effect on these optical imaging systems. In the following two sections, the influence of temperature variations on DIC/DVC measurements will be discussed theoretically and experimentally.

2.2. Influence of temperature variations on DIC/DVC: error analyses

2.2.1. Thermal errors in 2D-DIC and stereo-DIC

When the temperatures of digital cameras change due to self-heating effect or ambient temperature variations, the geometrical configuration inside these cameras would change accordingly. As shown in Fig. 2, temperature variations could induce slight thermal deformation of the mechanical components within cameras. As a result, positions of camera sensors and optical lenses may change accordingly, which means a slight change in imaging geometry. Thus, the images captured by a 2D-DIC imaging system may undergo slight alterations in position and magnification even though the test specimen is stationary. These thermal-induced image motions and deformations can be detected by DIC as virtual or artificial displacements and strains. Similarly, thermal errors also present in DIC measurement because of environmental temperature changes during prolonged outdoor experiments.

In most cases, both the sensor plane and imaging lens could continuously get close to the sample due to thermal deformations of the mechanical components within the camera and camera outer case, as evidenced in [38]. Assume that the original image distance and object distance are L_0 and Z_0, the out-of-plane motions of the sensor plane and the lens are Δd_S and Δd_L. These motions will introduce additional in-plane displacements and strains on the sensor plane. Using the imaging model indicated in Fig. 2, the resulting virtual strains, ε_x and ε_y, on the sensor plane can be determined as

$$\varepsilon_x = \varepsilon_y = \frac{Z_0}{L_0} \cdot \frac{L_0 + \Delta d_L - \Delta d_S}{Z_0 - \Delta d_L} - 1 = \frac{Z_0 \cdot \left(\Delta d_L - \Delta d_S\right) + L_0 \cdot \Delta d_L}{L_0 \cdot \left(Z_0 - \Delta d_L\right)} \quad (1)$$

Generally, Δd_L is far less than Z_0. Hence the above expression can be simplified as

$$\varepsilon_x = \varepsilon_y \approx \frac{\Delta d_L}{Z_0} + \frac{\Delta d_L - \Delta d_S}{L_0} \quad (2)$$

From the above analysis, it can be concluded that the uniform dilatational strains present, which are determined by both the thermal movements Δd_L, Δd_S of imaging hardware and the preset imaging arrangement Z_0, L_0.

In routine use of stereo-DIC system, static calibration model, which generally relies on the calibration images captured prior to the recording of experimental images, is adopted. Likewise, the two cameras utilized in stereo-DIC independently generate heat after being switched on, and the cameras would undergo temperature changes after initial calibration. In this case, the camera parameters of the stereo-DIC