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Whole-field thickness strain measurement using multiple camera digital image correlation system

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ABSTRACT

Three Dimensional digital image correlation(3D-DIC) has been widely used by industry, especially for strain measurement. The traditional 3D-DIC system can accurately obtain the whole-field 3D deformation. However, the conventional 3D-DIC system can only acquire the displacement field on a single surface, thus lacking information in the depth direction. Therefore, the strain in the thickness direction cannot be measured. In recent years, multiple camera DIC (multi-camera DIC) systems have become a new research topic, which provides much more measurement possibility compared to the conventional 3D-DIC system. In this paper, a multi-camera DIC system used to measure the whole-field thickness strain is introduced in detail. Four cameras are used in the system. two of them are placed at the front side of the object, and the other two cameras are placed at the back side. Each pair of cameras constitutes a sub stereo-vision system and measures the whole-field 3D deformation on one side of the object. A special calibration plate is used to calibrate the system, and the information from these two subsystems is linked by the calibration result. Whole-field thickness strain can be measured using the information obtained from both sides of the object. Additionally, the major and minor strain on the object surface are obtained simultaneously, and a whole-field quasi 3D strain history is acquired. The theory derivation for the system, experimental process, and application of determining the thinning strain limit based on the obtained whole-field thickness strain history are introduced in detail.

1. Introduction

Digital Image Correlation (DIC) was first proposed and developed by multiple researchers in the 1980s, including Peters [1], Sutton [2], and Yamaguchi [3]. The whole field displacement/deformation can be measured through tracking the motion in one small facet, then the whole-field strain can be calculated. In the first few decades, the research was mainly focused on using one fixed camera to perform DIC measurements. This method is known today as the two-dimensional (2D) Digital Image Correlation technique. However, since the single camera can only obtain two-dimensional information, the displacement/strain measurement is limited to the in-plane measurement of some planar components. Even in these special cases, a small out-of-plane displacement or deformation will introduce errors into the in-plane measurement result [4–6]. Starting in the mid-1990s, the three-dimensional (3D) Digital Image Correlation technique was proposed to overcome the drawbacks of the 2D-DIC technique. In the 3D-DIC technique, two fixed cameras with a set angle between them were placed in front of the test object, and the modified stereo-vision method was applied to combine the information from these two cameras [7,8]. At the same time, to determine the intrinsic and extrinsic parameters for the 3D-DIC system, the 3D calibration technique for the DIC system was investigated by many researchers [9–11].

Recently, the 3D-DIC technique has been successfully applied to many different areas. Chevalier L uses DIC to analyze the multiaxial behavior of rubber-like materials [12]. Helm uses 3D-DIC to determine the deformation in wide notched panels [13]. Many researchers have used DIC to determine the Forming Limit Diagram for new materials [14,15]. Xia, Bin, and Wu also make some progress in the single lens 3D DIC methods [16–21]. However, similar to other interferometry methods [22,23], because the conventional 3D-DIC technique can only measure a single surface on the test object, the obtained information in the depth direction is quite limited. This limitation prevents some important material properties from being tested. The whole field thickness strain measurement is a big challenge for strain measurement. Without this information, the thinning limit cannot be determined for new materials, which is an important criterion in sheet metal forming. The traditional method of measuring thickness strain, either

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by measuring the thickness change using a caliper during the test or attaching a tiny strain gauge on the side surface, is quite primitive. All of these methods have their limitations and cannot obtain the whole field thickness strain. In 2009, Moutrille M P applied DIC to capture the images on the side surface, then used the calculated minor strain on the side surface as the thickness strain [24]. Since the dimension in the thickness direction is much smaller compared to the length direction (ratio less than 1/10) for sheet metal, the image resolution makes the strain measurement using DIC on the side surface quite rough. Besides that, only the thickness strain on the edge side of the front surface can be obtained from the side surface, and the thickness strain in the remaining area on the front surface cannot be obtained. In 2015, Thorsten S proposed an idea to extend the conventional 3D-DIC system to the multi-camera DIC system using the cluster approach and estimated the error for the multi-camera DIC system [25,26]. The multi-camera DIC system provides more possibilities for the camera arrangement, which could extend its application to many new areas.

In this paper, a multi-camera DIC system used to measure the whole-field thickness strain is proposed, and the theory of the system is introduced in detail. A total of four cameras are used in the system. Two of the cameras are placed in front of the object, and the other two cameras are facing the back side. Each pair of cameras works as a sub stereo-vision system and measures the whole-field deformation on one side of the object. A special calibration plate is used to calibrate the four cameras at the same time, and the information from these two subsystems are linked with the calibration. With the combination of the deformation on both the front and back side, the whole field thickness strain is calculated. Also, a quasi 3D strain history can be directly obtained by combing the obtained major and minor strain on the surface. A standard tensile test is conducted to validate the system, and the whole-field thickness strain history is obtained. As an application, the thinning strain limit is determined directly by the obtained thickness strain, instead of using the volume conservation principle, as used in the traditional method, to calculate the thickness strain using principal strains ε_1 and ε_2 [27].

2. Principle of the whole-field thickness strain measurement DIC system

The whole-field thickness strain measurement DIC system consists of two subsystems. One subsystem measures the front surface of the object, and the other measures the back. The concept of the whole-field thickness strain measurement DIC system is shown in Fig. 1.

Each part is a typical two-camera stereo vision system, and these two subsystems are linked through calibration. By applying the perspective projection of the pinhole camera model, the transformation from image coordinate (2D coordinate) to camera coordinate (3D coordinate) for each camera can be expressed as shown in Eq. (1).

$$\alpha^i \vec{\mathbf{x}}^i_{image} = \mathbf{P}^i \cdot \vec{\mathbf{x}}^i_c,$$
$$\mathbf{P}^i = \begin{bmatrix} f^i & 0 & 0 & 0 \\ 0 & f^i & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \vec{\mathbf{x}}^i_{image} = \begin{bmatrix} x^i_{image} \\ y^i_{image} \\ 1 \end{bmatrix}, \vec{\mathbf{x}}^i_c = \begin{bmatrix} x^i_c \\ y^i_c \\ z^i_c \\ 1 \end{bmatrix} \tag{1}$$

where $\mathbf{P}^i$ is the projection matrix which projects the 3D coordinate to a 2D plane following the pinhole camera rule, α^i is the scale factor, f^i is the focus of the lens, $\vec{\mathbf{x}}^i_{image}$ and $\vec{\mathbf{x}}^i_c$ is the image coordinate and camera coordinate of the i_{th} camera, respectively.

In each sub stereo-vision system, the two camera coordinates need to be transformed to one single world coordinate system, and the distortion of the image due to the perspective angle need to be fixed. Therefore, the transformation between the i_{th} camera pixel coordinate to the world coordinate can be expressed in Eq. (2):

$$\vec{\mathbf{x}}^i_c = \mathbf{T}^i \cdot \vec{\mathbf{x}}^j_w$$
$$\mathbf{T}^i = \begin{bmatrix} \mathbf{r}^i & \mathbf{t}^i \\ 0 & 1 \end{bmatrix}, \mathbf{D}^i \cdot \mathbf{A}^i \cdot \mathbf{P}^i \cdot \vec{\mathbf{x}}^i_c = \alpha^i \vec{\mathbf{x}}^i_{image}$$
$$\mathbf{r}^i = \begin{bmatrix} r^i_{11} & r^i_{12} & r^i_{13} \\ r^i_{21} & r^i_{22} & r^i_{23} \\ r^i_{31} & r^i_{32} & r^i_{33} \end{bmatrix}, \mathbf{t}^i = \begin{bmatrix} t^i_x \\ t^i_y \\ t^i_z \end{bmatrix} \tag{2}$$

where $\mathbf{T}^i$ represents the transformation matrix that transforms the camera coordinate to the world coordinate of the sub stereo-vision system, $\mathbf{r}^i$ is the rotation component and t^i is the translation component in the transformation matrix. $\mathbf{D}^i$ and $\mathbf{A}^i$ is the distortion and skew adjust matrix, which could be determined using different distortion or skewed models. $\vec{\mathbf{x}}^j_w$ is the world coordinate to the corresponding sub stereo-vision system.

Since the whole-field thickness strain measurement DIC system contains two sub stereo-vision systems, thus the whole system has two world coordinates. $\vec{\mathbf{x}}^{\mathrm{f}}_w$ stands for the world coordinate of the front subsystem, and the $\vec{\mathbf{x}}^{\mathrm{b}}_w$ stands for the world coordinate of the back subsystem. Camera 1 and camera 2 belongs to the front subsystem, and the camera coordinate $\vec{\mathbf{x}}^1_c$ and $\vec{\mathbf{x}}^2_c$ transforms to the world coordinate $\vec{\mathbf{x}}^{\mathrm{f}}_w$. Cameras 3 and 4 belong to the back subsystem, and the camera coordinate $\vec{\mathbf{x}}^3_c$ and $\vec{\mathbf{x}}^4_c$ transforms to the world coordinate $\vec{\mathbf{x}}^{\mathrm{b}}_w$.

The last step is connecting these two world systems into one single global system $\vec{\mathbf{x}}_g$. For simplicity, the global system $\vec{\mathbf{x}}_g$ is established directly using the information from one of the world systems (e.g. $\vec{\mathbf{x}}^{\mathrm{f}}_w$). In this case, the world system on the back side needs to be transformed into the global system to perform further evaluation. This transform can be performed using a transform matrix $\mathbf{T}_w$, as shown in Eq. (3).

$$\vec{\mathbf{x}}_g = \vec{\mathbf{x}}^{\mathrm{f}}_w = \mathbf{T}_w \cdot \vec{\mathbf{x}}^{\mathrm{b}}_w \tag{3}$$

3. Calibration of the whole-field thickness strain measurement DIC system

The focus of the camera lens, the distortions, the location of cameras, etc. are unknown for each sub stereo-vision system. There are five intrinsic parameters and six extrinsic parameters with certain views that need to be determined to fulfill the coordinate transformation. All of these parameters need to be determined by calibration. Additionally, the two world coordinate systems need to be connected or combined into one single world system to combine the information obtained on the front side and back side. Compared with the conventional 3D-DIC system, four cameras need to be calibrated at the same time, and the relation between two world coordinate system need to be

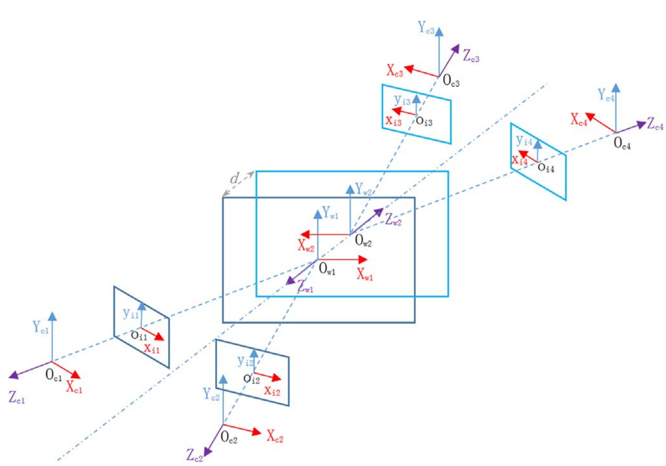

Fig. 1. Scheme of whole-field thickness strain measurement DIC system.