

Chapter 4

On the In-Plane Displacement Measurement by 3D Digital Image Correlation Method

Chi-Hung Hwang, Shou Hsueh Wang, and Wei-Chung Wang

Abstract In this study, a three-step object was moved in-plan to different positions and determined the displacement by 3D DIC method. To monitor the out-of-plane displacement of the object during movement, a laser triangulation method was performed together with a typical 3D DIC. The laser triangulation setup consists of a laser source with a cylindrical lens mounted on the center of the camera-pair to generate a line pattern and then the discontinuous line patterns were then recorded by left- and right- cameras for step-height calculation. The measurement results reveal that there is displacement deviation introduced by viewing angle between camera and the object as the object is positioned at different locations. The experiment also shows that the deviation of 3D DIC determined in-plane displacement is small but the determined displacement is higher than the nominal displacement determined by a precision stage; in addition, out-of-plane displacements have been reported and cannot be ignored. In the final, a single camera model based on geometrical parameters of 3D DIC is proposed to correct the 3D DIC determined displacements; according to current results, the in-plane displacement of the 3-steps object can be tremendously reduced from 9.7% to 1.7%.

Keywords 3D DIC • In-plane displacement • Laser triangulation method • Different depths • Step high

4.1 Introduction

Digital image correlation (DIC) method becomes essential optical measurement method because DIC method is one of noncontact measurement methods which can be implemented for industrial and other on-site applications. The principle of DIC method is based on tracking artificial or natural surface random pattern among series captured images, therefore, two images from different status are needed for evaluating the change from one frame to the others, which means the associated displacement, strain and stress can be evaluated from two images captured or extracted from the recorded video stream. Moreover, the “image” is not limited to the traditional picture captured by the optical lens; for DIC method, the so called “image” has been successfully extended to two dimensional/ three dimensional spatial digital data which are obtained by SEM, TEM, AFM and XCT for micro-scale, nano-scale and volume object respectively. DIC methods can be classified into 2D DIC and 3D DIC method according to the optical system used for capturing optical images for analysis.

There are possible errors could be introduced by 2D DIC method unless surfaces of objects under testing are flat, the camera is perpendicular aligned with respect to the specimen and in-plane displacement [1–3]. In general, 3D DIC which is based on the stereo-photogrammetry has been considered as the solution to eliminate errors introduced by out-of-plane displacement [1, 3–5] because the visual triangulation introduced by stereo-images can provide extra data to reconstruct the depth information of the test object. Different from previous studies, in this paper, a three-step aluminum block is manufactured as a test object which was moved in-plane with well aligned precious linear stage along x-axis to evaluate the 3D DIC measurement accuracy of in-plane displacement through depth-direction. By using the images obtained by the camera-pair setup, distance from camera-pair to the aluminum block and the DIC software, the measurement results showed that the in-plane displacement between the 3D DIC determined one is extremely large than the nominal in-plane displacement, moreover, out-of-plane displacement was also presented. Be aware of this new challenge, the measurement differences were discussed and then a model was proposed to correct the 3D DIC determined in-plane displacement.

C.-H. Hwang (✉)
ITRC, NARL, Hsinchu, Taiwan, 30073, Republic of China
e-mail: chhwang@itrc.narl.org.tw

S.H. Wang • W.-C. Wang
Department of Power Mechanical Engineering, National Tsing Hua University, Hsinchu, Taiwan, 30013, Republic of China

4.2 Experimental Setup

In this study, a typical 3D DIC configure composed with a laser triangulation setup were implemented for in-plane displacement measurement, as shown in Fig. 4.1. The laser triangulation setup consisted of a laser source and a cylindrical lens which were integrated as an unit and then mounted right at the center in between left- and right- cameras; based on the experimental setup, two cameras can be used to take image-pairs for determining in-plane displacement by using 3D DIC method; at the same time, the left- and right- cameras can also capture a bright curve introduced by the projected laser light-sheet intersects with the specimen. The heading angles of the left- and right- cameras are rotated to be about $\pm 10.5^\circ$ with respect to the specimen. The baseline distance of the two cameras is set to be about 188.6 mm.

A three-step aluminum block was used as the test specimen, the change of height indicates the geometrical change of the experimental setup which can be used to monitor the change of the geometrical setup. The sizes of the three-step specimen are $10 \times 10 \text{ mm}^2$, $30 \times 30 \text{ mm}^2$ and $60 \text{ mm} \times 70 \text{ mm}^2$ with respect to the front surface, the middle surface and the rear surface, and the offsets of front-to-middle surface and middle-to-rear surface are 10.18 mm and 20.25 mm respectively.

For 3D DIC in-plan study, the three-step-height specimen was moved by a manual linear-stage along x-axis away 3, 6, 9, 12, 15, 18, 21 and 24 mm with respect to its origin. As shown in Fig. 4.2, the displacements were extracted from three

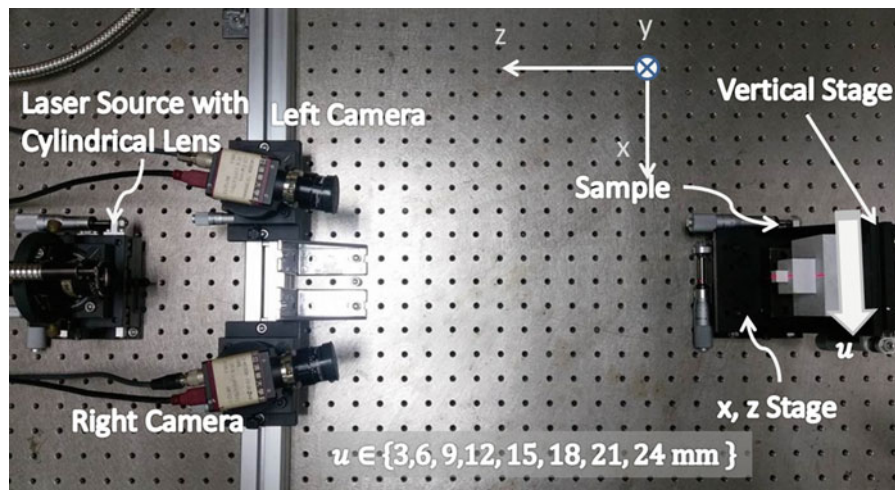


Fig. 4.1 Experimental setup consists of the 3D DIC and the laser triangulation method

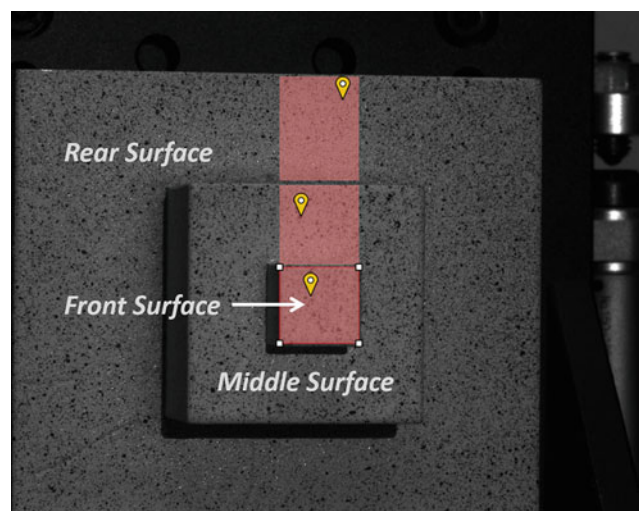
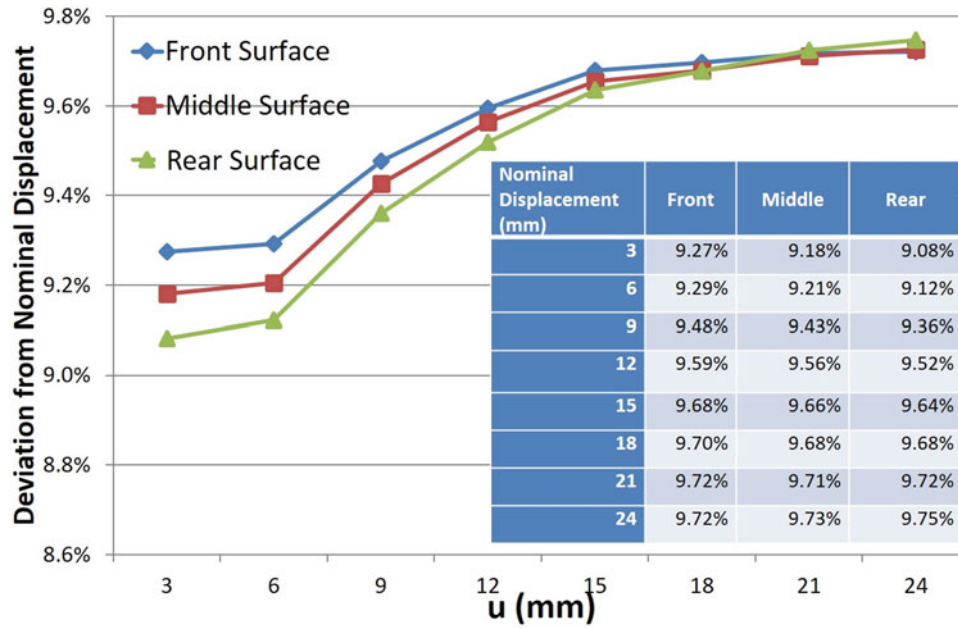


Fig. 4.2 A three-step aluminum block is moved in plan along x-direction and the displacement is evaluated from remarked regions of the block by 3D DIC method

Table 4.1 Calibrated parameters of camera-pair

Parameters	C_x	C_y	f_x	f_y	Skew	κ_1	κ_2	κ_3
Left camera	783.22	525.51	8709.47	8707.76	-1.4528	-0.2015	0	0
Right camera	819.33	512.09	8718.95	8717.76	-1.7855	-0.2026	0	0

**Fig. 4.3** In-plan displacement derivations with respect to nominal displacement-raw data

surfaces, named as front, middle and rear surface, and averaged over the each area of each surface. The displacements were determined by using a commercial DIC system VIC 3D, the camera-pair has calibrated by proposed calibration procedures and the associated parameters were shown in Table 4.1.

4.3 Results and Discussions

In this study, the in-plane displacement was first determined by using 3D DIC with 27×27 pixels subset. Different from previous studies, a three-step specimen is used instead of a plate. Because of the surfaces are located at different depths, therefore, 3D DIC determined in-plane displacements can be obtained across the depths at the same time. Considering rotation along y-axis might be introduced while moving the test specimen along x-axis, a laser triangulation method was implemented in this study and the two available cameras captured the images from left- and right- views to monitor the movement. The detail measurement results are presented and discussed by the following sections.

4.3.1 In-Plane Displacements at Different Depths

The determined in-plane displacements at different surfaces were illustrated in Fig. 4.3, the results showed that the deviations between the determined in-plan displacements and nominal displacements are always larger than 9%, and the deviations are increasing as the in-plane displacement enlarged. The illustrated Fig. 4.3 also revealed very interesting informations; the deviations from nominal in-plane displacement in magnitude are ordered as $\Delta u|_{\text{front surface}} > \Delta u|_{\text{middle surface}} > \Delta u|_{\text{rear surface}}$ when the object was moved from 0 to 21 mm; in fact, the deviation difference among three surfaces at a given nominal in-plane displacement also decreases when the object is moved from 0 to 21 mm and the deviation is almost the same for all three surfaces as the nominal in-plane displacement is 21 mm in this study.

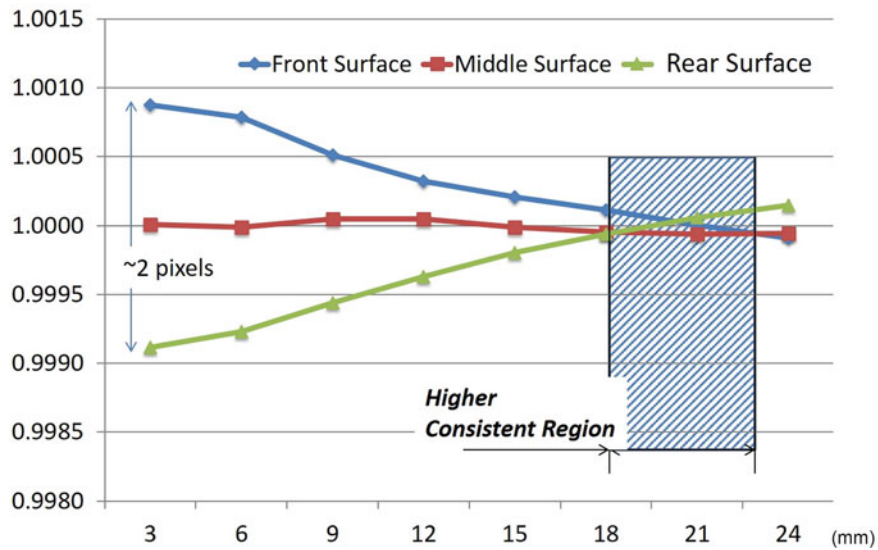


Fig. 4.4 The ratios of 3D DIC determined in-plane displacement u w.r.t averaged in-plane displacement

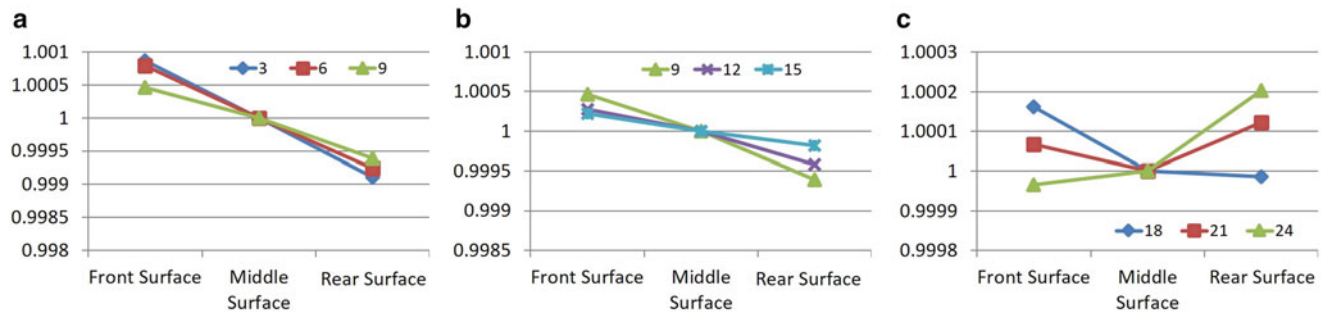


Fig. 4.5 Normalizing in-plane displacement u of different surface w.r.t 3D DIC determined displacement of middle surface. (a) Moving towards $+x$ - axis to 3, 6 and 9 mm. (b) Moving towards $+x$ - axis to 9, 12 and 15 mm. (c) Moving towards $+x$ - axis to 18, 21 and 24 mm

Figure 4.4 is the illustration of the determined in-plane displacements of all three surfaces are compared with the averaged values. The results show that the maximum deviation is about 2 pixels which happened to be moving the aluminum block 3 mm away from its origin and then decreased as the displacement increased until the in-plane displacement is 21 mm. It should be emphasize that the deviation-differences can be identified however the difference of the determined in-place displacement in magnitude among three surface are small. Moreover, inspecting Fig. 4.4 carefully, it could be fund that the averaged displacement is closed to the middle surfaces because the middle surface-to-averaged in-plane displacement is 1 with small fluctuation which means the 3D DIC evaluated in-plane displacement can be approximated by the data of middle surface. In addition, Fig. 4.4 also implied that the determined in-plane displacement might be a function of depth. Pleas also be award that the determined in-plane displacement is over 9% higher than the nominal one, therefore, it is important to know that the determined in-plane displacement near the camera-pair is higher/ lower than the determined displacement related far from the camera-pair, by this way the measurement can be improved by increasing/ decreasing the distance between the camera-pair and object or additional in-plane displacement calibration should be performed to ensure the distance between the camera-pair and the testing object is proper.

Since the middle surface can be used as a reference of measurement, the measured in-plane displacement of rear and front surfaces are normalized with respect to the middle surface one and the results are shown in Fig. 4.5. By comparing the plotted curves, interesting to know, in this study, that the ratio can be described as a linear function for small in-plane displacement, in this study, from 3 to 15 mm. The slope of the estimated linear functions decreased in magnitude as the in-plane displacement was increased, and then when the determined in-plane displacement is large then 15 mm, then the determined in-plane displacement from front- to rear- surfaces cannot be considered as linear; eventually, the determined in-plane displacement of rear- surface become higher- than the front surface.

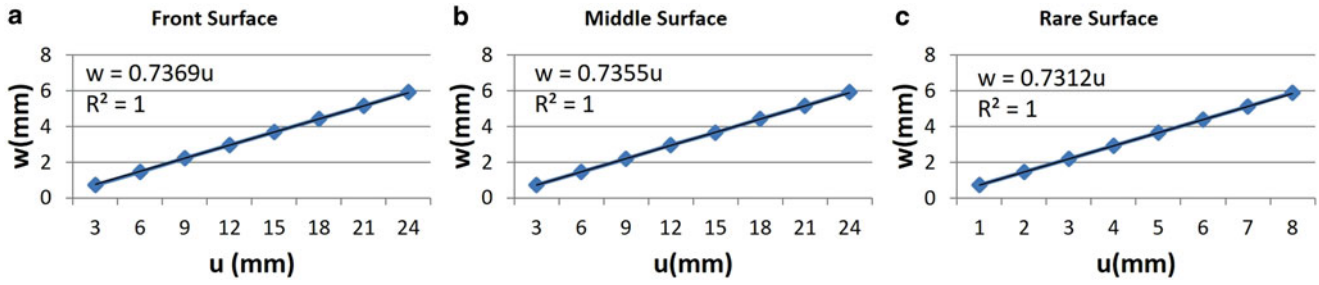


Fig. 4.6 Associated out-of-plane displacement by 3D DIC as the object is moved in-plane. (a) Front surface. (b) Middle surface. (c) rare surface

Table 4.2 $(\Delta\bar{w})/(\Delta\bar{u})$ versus nominal displacement u

Nominal Displ. u	Averaged Displacement		$\Delta\bar{w}/\Delta\bar{u}$	$\theta = \tan^{-1} \frac{\Delta\bar{w}}{\Delta\bar{u}}$
	$\Delta\bar{w}$	$\Delta\bar{u}$		
3	–	–	–	–
6	0.7301	3.2770	0.2228	12.5604
9	1.4623	6.5725	0.2225	12.5430
12	2.1975	9.8718	0.2226	12.5499
15	2.9278	13.1732	0.2223	12.5308
18	3.6746	16.4677	0.2231	12.5790
21	4.4183	19.7653	0.2235	12.6006
24	5.1615	23.0602	0.2238	12.6164
Averaged angle θ				12.5686

4.3.2 Out-of-Plane Displacement

Although the testing object was moved along x-axis, out-of-plan displacement was obtained from 3D DIC analyzed results. In this study, the out-of-plane displacement was increased as the in-plane displacement increased. As shown in Fig. 4.6, the out-plane displacement and in-plane displacement can be well fitted by a linear function. The slope of the fit curves are 0.7369, 0.7355 and 0.7312 with respect to front-, middle- and rear- surfaces and the corresponding R^2 can be approximated to be 1. In addition, the slope of u-w plots are fitted with respect to the step-height difference by using front-surface as a reference, again, the step-high difference (Δh) versus u-w slope (s) can be described as $s = -60 \times 10^{-6} \Delta h + 0.2457$ with corresponding $R^2 = 0.9822$.

Table 4.2 presents a very interesting result regarding the averaged in-plane displacement ($\Delta\bar{u}$) and the averaged out-of-plane displacement ($\Delta\bar{w}$) with 3 mm nominal averaged in-plane and out-of-plane displacement as reference. The results show that the calculated $(\Delta\bar{w})/(\Delta\bar{u})$ values are always about 0.2223 which means the increment of w is highly dependent with u . Meanwhile the $(\Delta\bar{w})/(\Delta\bar{u})$ ratio can be converted to an angle defined by u and w . The angle is about 12.5686° and this angle is close to the 10.5° heading angle of camera. In fact, the estimated angle defined by displacement u and w could be the implemented heading angle of the camera used for 3D DIC, however, more evidences based on experimental results before conclusion.

4.3.3 Laser Triangulation Measurement

As indicated in 3.2, the out-of-plane displacement can be evaluated by 3D DIC while the object was moved in-planes along x-axis. Although the movement is performed by using a precision stage, however, monitoring the possible out-of-plane displacement caused by geometrical misalignment of camera-pair and testing object is essential. In this study, a laser and cylindrical lens integrated light source was moved together with the aluminum block, the step height of the aluminum block was then evaluated from left- and right- cameras; by this way, if there is unparallel available between the precious stage and base-line of camera-pair, then the unparallel can be detected because of the change of height between steps of the specimen. The measurement results were shown in Fig. 4.7, the height difference between front- and middle- surfaces obtained from left- and right- cameras are almost identical when the displacement is less than 10 mm; but the difference of evaluated

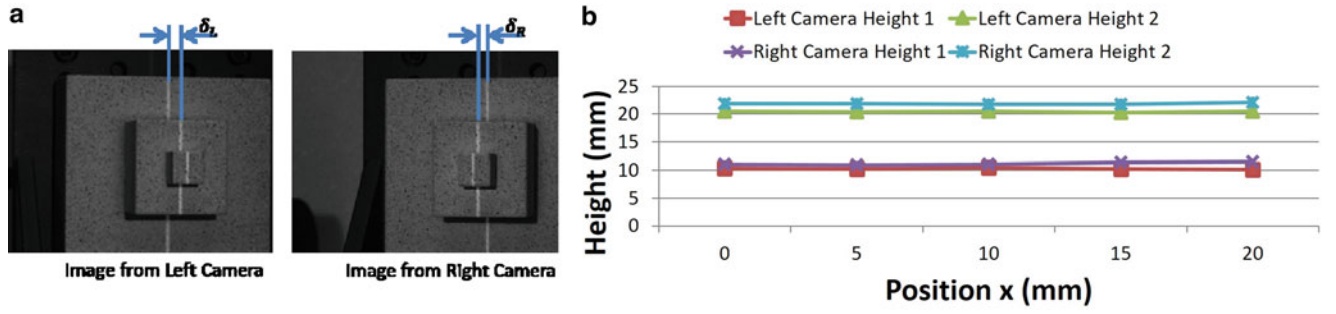


Fig. 4.7 The depths of an aluminum block evaluated by using laser triangulation methods at different x-positions. (a) Typical images obtained from Left- and Right cameras used for depth evaluation by laser triangulation method. (b) The depths observed from left- and right- cameras as the object is moved along +x-direction to different positions

height were enlarged as the in-plane displacement increased. Meanwhile, the step-height between front- and middle- surface determined from left- camera is slightly decreased as the in-plane displacement increased, but the height determined by the right-camera is converse. As for the determined height between middle- and rear- surfaces, the determined heights from both left- and right- cameras at different locations along x-axis are departure from each other, however the offsets are almost the same in this study.

In this study the out-of-plane runoff caused by moving the object along the linear stage should be ignored. Considering the determined out-of-plane displacement is monotonously increased as the in-plane displacement increased which means there is a small angle introduced by the precision stage and the structure used to support the camera-pair. However, from laser triangulation measurement results, the height of middle- and rear-surface remain the same value as the object move from 0 to 20 mm away from its origin; the heights of front- and middle- surface were different at different locations along x-axis and the maximum difference is about 1.36 mm which is small than the corresponding out-of-plane displacement determined by 3D DIC.

4.3.4 Correcting the In-Plane Displacement

According to the measurement results presented previously, the evaluated in-plane displacement is 9% above the nominal in-plan displacement and the out-of-plane displacement is available with about 1/4 in-plane displacement in magnitude. In addition, according to laser triangulation measurement, the aluminum block was moved by a precision stage should be moved toward x-axis parallel to the camera-pair baseline; that means there is no significant out-plane displacement will be introduced as the measurement is executed. Since the angle defined by in-plane and out-of-plane displacement is almost a constant all over the displacement range, therefore, the deviation of in-plane displacement and the associated unforeseen out-of-plane displacement are considered to be introduced by the cameras layout. To correct the deviation, a single pinhole-camera model with half-baseline distance and the heading angle with respect to the object is 12.5686° which is introduced by $\Delta\bar{u} - \Delta\bar{w}$ to simplify the camera-pair implemented for 3D DIC imaging system. Then, in this study, the in-plane displacement can be corrected by the following equation,

$$u \sim \frac{\bar{b} + \bar{u}}{\cos(\phi + \varphi)} \cos(\theta + \varphi + \phi) - b \quad (4.1)$$

Where θ is the angle defined by $\Delta\bar{u} - \Delta\bar{w}$, φ is angle spand by half baseline of the camera-pair with angle vertex at pinhole, ϕ is the angle spand by in-plane displacement along x-axis with its vertex locates at pinhole, b is the half baseline of camera-pair, \bar{b} is defined to be distance of baseline b projecting with angle φ along the direction of $\Delta\bar{u}$. Assuming b and distance between pinhole and object are known, then the angle φ and \bar{b} can be determined. As shown in Fig. 4.8, the blue line is the in-plane displacement deviation with respect to the nominal one and the red line is the in-plane displacement deviation which is corrected by Eq. (4.1). The results show that the maximum difference in magnitude between the nominal displacement and evaluated in-plane displacement before and after correcting both occur when the block aluminum is moved

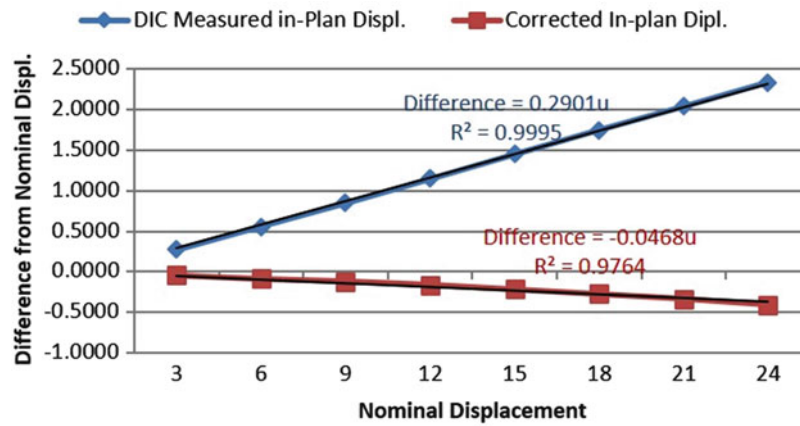


Fig. 4.8 Different from nominal in-plane displacement before/after proposed geometrical correction model

24 mm away from its original location. Before correcting, the evaluated in-plane displacement is monotonously increased as the nominal in-plane displacement increased and the maximum difference is up to 2.3 mm larger than the nominal one which leads to 9.7%; controversy, the modified in-plane displacement is a little below the nominal in-plane displacement and the difference is monotonously decreased as the nominal in-plane displacement increased and the maximum difference is about 1.7% which is equivalent to 0.41 mm.

4.4 Conclusions

In this study, an in-plane displacement of a three-step aluminum block is determined by using 3D DIC method. The measured in-plane displacement in magnitude is much higher than the nominal in-plane displacement which is performed by moving the aluminum block with a precious linear stage. The difference between the 3D DIC determined in-plane displacement and nominal in-plane displacement was reported to be monotonously increased as the nominal in-plane displacement increased and the maximum difference is about 9.7% at nominal in-plane displacement is 24 mm. In addition, thanks to the aluminum block consists of three surfaces at different depths, the change of in-plane displacement at different depths can be determined at the same time. The results in this study present that the displacement determined by front- surface which is close to the camera-pair is highest for small displacement and the corresponding in-plane displacement of rear-surface, far away from the camera, is smallest. The results indicate the 3D DIC determined in-plane displacement is sensitive to the distance between the object and camera-pair. Meanwhile, from the 3D DIC evaluated displacement field, out-of-plane displacement was also reported. Again, the out-of-plane is monotonously increased as the nominal in-plane displacement increase. The ratios of the 3D DIC determined in-plane displacements and out-of-plane displacements at different nominal in-plane displacements are almost constant, in this study, which implied that the precious linear stage might be unparallel with respect to the frame used to support camera-pair for capturing the stereo-images or a no revealed characteristic of 3D DIC method. To identify the possible reason, a laser triangulation method was implemented with left- and right- camera was used to imaging the laser patterns on the aluminum block. The results obtained by using laser triangulation method indicate that the aluminum block is moved along precious linear stage without introduced out-of-plane displacement with respect to the geometrical setup of the camera-pair, therefore, according to current evidence, the out-of-plane displacement could be a characteristic 3D DIC method and the way to correct the 3D DIC determined in-plane displacement is essential. Based on a single camera model, a method to correct 3D DIC determined in-plane displacement was presented. The maximum difference between the determined in-plane displacement and the nominal in-plane displacement is improved from 9.7% to 1.7% in ratio and the corresponding displacements are 2.30 and 0.41 mm.

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Dr. Hwang works for Instrument Technology Research Center, NARLabs as a research fellow and now he also serves as Division Director of Applied Optics Division.