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Experimental investigation of the systematic error on photomechanic methods induced by camera self-heating

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Abstract: The systematic error for photomechanic methods caused by self-heating induced image expansion when using a digital camera was systematically studied, and a new physical model to explain the mechanism has been proposed and verified. The experimental results showed that the thermal expansion of the camera outer case and lens mount, instead of mechanical components within the camera, were the main reason for image expansion. The corresponding systematic error for both image analysis and fringe analysis based photomechanic methods were analyzed and measured, then error compensation techniques were proposed and verified.

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References and links
1. W. N. Sharpe, Handbook of Experimental Solid Mechanics (Springer, 2007).
2. H. W. Schreier, M. A. Sutton, and J. Orteu, Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications (Springer, 2009).
3. B. Pan, K. M. Qian, H. M. Xie, and A. Asundi, “Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review,” Meas. Sci. Technol. 20(6), 062001–062017 (2009).
4. X. Wang, Q. W. Ma, S. P. Ma, and H. T. Wang, “A marker locating method based on gray centroid algorithm and its application to displacement and strain measurement,” in Proceedings of IEEE Conference on Intelligent Computation Technology and Automation (Institute of Electrical and Electronics Engineers, 2011), pp. 932–937.
5. M. Halioua, R. S. Krishnamurthy, H. Liu, and F. P. Chiang, “Projection moiré with moving gratings for automated 3-D topography,” Appl. Opt. 22(6), 850–855 (1983).
6. J. N. Petzing and J. R. Tyrer, “Recent developments and applications in electronic speckle pattern interferometry,” J. Strain Anal. Eng. Des. 33(2), 153–169 (1998).
7. D. Post, B. Han, and P. Ifju, High Sensitivity Moiré: Experimental Analysis for Mechanics and Materials (Springer, 1994).
8. K. Ramesh, T. Kasimayan, and B. N. Simon, “Digital photoelasticity - A comprehensive review,” J. Strain Anal. Eng. Des. 46(4), 245–266 (2011).
9. K. W. Wong, M. Lew, and Y. Ke, “Experience with two vision systems,” Proc. SPIE 1395, 3–7 (1990).
10. H. A. Beyer, Analysis of a CCD-camera based Photogrammetric Close-range System, Ph.D. Thesis, ETH-Zurich, 1992.
11. H. Handel, “Analyzing the influences of camera warm-up effects on image acquisition,” IPSJ Trans. Comput. Vis. Appl. 1, 12–20 (2009).
12. S. P. Ma, J. Z. Pang, and Q. W. Ma, “The systematic error in digital image correlation induced by self-heating of a digital camera,” Meas. Sci. Technol. 23(2), 025403 (2012).
13. R. C. Gonzalez and R. E. Woods, Digital Image Processing (Prentice-Hall, 2002).
14. K. Nishimura, H. Miyachi, K. Fuzise, T. Otani, S. Okada, and H. Yokogawa, “Measurement of polished curved surfaces with tele-microscope,” Trans. Soc. Instrum. Control Eng. 30(10), 1260–1262 (1994).
15. H. A. Bruck, S. R. McNeill, M. A. Sutton, and W. H. Peters III, “Digital image correlation using newton-raphson method of partial differential correction,” Exp. Mech. 29(3), 261–267 (1989).
16. Q. Kemao, “Two-dimensional windowed Fourier transform for fringe pattern analysis: Principles, applications and implementations,” Opt. Lasers Eng. 45(2), 304–317 (2007).
1. Introduction

Photomechanics [1] includes the experimental methods used to resolve stress or deformation fields from images, either by directly analyzing the images themselves or by analyzing the interferometric fringes on the images. Digital Image Correlation (DIC) [1–3], digital marker based optical extensometer [1,4], and other similar techniques belong to the image analysis category, whereas projection fringe profilometry [1,5], electronic speckle pattern interferometry [1,6], moiré [1,7] and photoelasticity [1,8], etc., belong to the fringe analysis category; for both categories, images are the basic data for the methods. Different from the traditional film based image recording methods of several decades ago, digital CCD and CMOS cameras (both referred to as digital cameras hereafter) have become the most common data acquisition instruments for photomechanics nowadays. Obviously, any unexpected errors on captured images caused by the digital camera will induce errors in the measured photomechanic results.

Recently, the errors on images caused by self-heating of the digital camera have caught the attention of various researchers. Wong, et al. [9] and Beyer [10] reported an error of one-tenth of a pixel image translation within the first hour of the camera being switching on, with the temperature of the camera increasing by about 10 degrees. Handel [11] extensively studied the image translation caused by camera self-heating and proposed a model to explain its origin whereby the image translation is caused by the thermal expansion of the mechanical components within the camera. The author has studied the error in DIC [12] caused by the self-heating of the digital camera and concluded that camera self-heating also induces a positive strain error which is more prominent than the pixel translation error. The strain error can be as large as 150 με over a temperature increase of 10 degrees, which is large enough to be significant in most measurement situations. The positive strain error indicates that the image experiences an expansion during camera self-heating and the temperature of the camera increases. It can be shown that the expansion of images not only induces a systematic error in DIC, but also in all other photomechanic methods. For image analysis methods, the situation is the same as that for DIC, whereas for fringe analysis methods, image expansion will slightly change the pitch of the fringes hence inducing errors in the phase calculation. As in the resistance strain gauge measurement [1], the temperature variation will also induce a notable error in photomechanic methods, such that temperature compensation should also be applied in order to eliminate the error.

In this paper, the study of self-heating induced image expansion for a digital camera is described. A new physical model to explain the mechanism of image expansion is proposed based on results from a specially designed experiment which shows that the thermal expansion of the lens mount, instead of the mechanical component within the camera [11], is the main reason for this. Within the model, the errors for both the image analysis category and fringe analysis category are derived and analyzed. The temperature induced errors are then experimentally measured and verified for various photomechanic methods and, finally, the error compensation techniques are discussed and verified.

This paper is organized as follows: In section 2, the self-heating which causes the temperature variation of the camera is analyzed, a physical model to explain the temperature induced image expansion is proposed and verified. In section 3, the temperature induced errors for different photomechanic methods are analyzed and measured. And in section 4, a temperature compensation technique is proposed and examined.

2. Principle for image expansion induced by self-heating of the digital camera

2.1 Temperature variation of a digital camera during experimentation

It is well known that the self-heating of a digital camera will cause an apparent temperature variation over a long period of image capture. Figure 1(a) shows a typical temperature increase curve of a digital camera (a IPX-16M3-L CCD camera with a Sigma macro 105 mm
F2.8DG lens) during an experiment, demonstrating that the camera experiences a heating-up stage followed by a heat balance stage. For this camera, the temperature of the case increased by about 10 degrees in the first 1.5 hours and then remained stable and, correspondingly, the lens mount increased by about 5 degrees although the temperature of lens stayed almost stable during the whole process (as shown in Fig. 1(b)). Measurements of other types of digital camera showed similar behavior; the temperature of the lens mount increased with that of the camera case which is lower, such that the temperature increase of the imaging system is described by the camera case for a given camera hereafter. In comparison with the camera case and mount, the temperature increase of the lens is quite small and can be ignored. The very low thermal conductivity of the lens material and the many gaps between the different parts of the lens could explain its very low temperature increase during self-heating of the camera.

![Figure 1](image1.png)

**Fig. 1.** The measured temperature variation of the camera case, mount and lens during prolonged image capturing showing (a) the temperature monitored by the thermal sensors and (b) the temperature monitored by the infrared camera. The experiment was performed at room temperature (20°C), with the temperature plotted on the Fig. being the net increase of temperature over room temperature. All of the following Figs. follow the same convention.

2.2 Temperature induced motion of the different parts of a digital camera

Experiments described in the section above show that the camera outer case and lens mount experience a relatively large temperature variation within the first 1.5 to 2 hours after the camera has been switched on, with the thermal expansion of the different parts of the camera slightly changing the optical path of the camera. The two pictures in Fig. 2(a) show the typical mechanical structure of a digital camera, typically a metal cube with an integrated circuit and the CCD sensor and lens mount fixed on the sides of a front plate. It is expected that the cube and lens mount will expand as the temperature of the camera increases, such that the motion of the different parts of the camera is as shown in Fig. 2(b).

![Figure 2](image2.png)

**Fig. 2.** Analysis of the motion of the different parts of a digital camera during self-heating showing (a) the structure of the digital camera (Imperx-16M3-L CCD camera) and (b) the observed motions.

An experiment was performed to verify the above analysis. As shown in Fig. 3, the Imperx-16M3-L digital camera, with a Sigma macro 105 mm F2.8DG lens, was fixed to a vibration-isolation platform and switched on. A thermal sensor was bonded to the top of the
camera to monitor the temperature variation and three Laser Displacement Sensors (LDS) were used to measure the motion of the different parts of the camera; LDS 1# and LDS 2# for the motion of front plate and back plate respectively, and LDS 3# for the motion of lens. A mechanical extensometer was used to measure the motion of the outer case (the cube) of the camera. The experiment was repeated three times, and the data recording for each experiment lasted about 2 hours. The experimental results are shown in Fig. 4.

![Experimental arrangement](image1.png)

**Fig. 3.** The experimental arrangement used to measure the motion of the different parts of the camera showing (a) the schematic and (b) the experimental setup.

![Experimental setup](image2.png)

**Fig. 4.** The motion of the different parts of camera during self-heating showing (a) the motion of the different parts and (b) the linear relationship between the motion of imaging sensor, lens and temperature. The experiment was performed at room temperature of 18°C.

Figure 4(a) shows that the outer case of the camera experienced an expansion as the temperature increased; the front plate moved forwards and the back plate moved in the opposite direction. The total displacement of the front and back plates are equal to the extensometer deformation that verifies the validity of the results. It is notable that the displacement of the lens, $\delta_{\text{lens}}$, is larger than that of the front plate, which should be equivalent to the motion of the CCD sensor, $\delta_{\text{CCD}}$. The difference between $\delta_{\text{lens}}$ and $\delta_{\text{CCD}}$ could be induced by the expansion of the lens mount, which is verified experiencing a similar temperature increase process. Figure 4(b) shows that both $\delta_{\text{lens}}$ and $\delta_{\text{CCD}}$ have a very good linear relationship with the variation of the camera temperature, such that two parameters, the slope of the $\delta_{\text{CCD}}$ and $\delta_{\text{lens}}$ curves, can be used to represent the degree of motion as follows;

$$k_{\text{CCD}} = \frac{\delta_{\text{CCD}}}{T},$$  \hspace{1cm} (1)

$$k_{\text{lens}} = \frac{\delta_{\text{lens}}}{T}.$$  \hspace{1cm} (2)
It can be seen that $k_{CCD}$ is mainly affected by the outer case of the camera, and $k_{lens}$ is mainly affected by the lens mount. Obviously, a longer lens mount will induce a larger $k_{lens}$ than that induced by a shorter mount, if they are manufactured by same material.

2.3 Physical model for temperature induced image expansion

![Fig. 5. A physical model to describe temperature induced image expansion showing (a) the definition of each variable and (b) the model.](image)

The motion of the imaging sensor and lens during the temperature increase of the camera can be simplified as shown in Fig. 5. Considering that $\delta_{lens} \gg \delta_{CCD}$, the model indicates a decrease of object distance $u$ and an increase of imaging distance $v$. According to the image geometry, this induces an image expansion, which can be calculated as

$$\frac{h'}{h} = \frac{u(v + \delta_{lens} - \delta_{CCD})}{v(u - \delta_{lens})},$$  \hspace{1cm} (3)

where $h'$ and $h$ are the size of the image before and after the temperature increase.

The relative image expansion $\alpha_e$ can be defined as

$$\alpha_e = \frac{h' - h}{h} = \frac{u(\delta_{lens} - \delta_{CCD}) + v\delta_{lens}}{v(u - \delta_{lens})}.$$  \hspace{1cm} (4)

Because $\delta_{lens} \ll u$, Eq. (4) can be simplified as

$$\alpha_e = \frac{\delta_{lens}}{u} + \frac{\delta_{lens} - \delta_{CCD}}{v}.$$  \hspace{1cm} (5)

From Eqs. (1) and (2), $\alpha_e$ can be expressed as

$$\alpha_e = \left(\frac{k_{lens}}{u} + \frac{k_{lens} - k_{CCD}}{v}\right)T = \alpha_T,$$  \hspace{1cm} (6)

where

$$\alpha_T = \frac{k_{lens}}{u} + \frac{k_{lens} - k_{CCD}}{v},$$  \hspace{1cm} (7)

is named as the image expansion rate. From Fig. 5(a) and Eq. (7), It can be concluded that $\alpha_T$ is affected by both the imaging hardware, i.e., $k_{CCD}$, $k_{lens}$ and $v$, and the imaging arrangement, i.e., $u$.

For an imaging system in the telephoto optical path, i.e., $u \gg v$, Eq. (7) could be simplified and the image expansion rate at this imaging arrangement could be expressed as,

$$\alpha_{T_w} = \frac{k_{lens} - k_{CCD}}{v}.$$  \hspace{1cm} (8)
This means that the imaging expansion rate can be a constitutive parameter of the imaging hardware for the imaging system in the telephoto optical path.

An experiment was designed to verify the above model with the arrangement of the experiment as shown in Figs. 6(a) and 6(b). A chessboard target was fixed on a stable, vibration-isolating platform with the digital camera (Imperx-16M3-L with a Sigma macro 105 mm F2.8DG lens) fixed on the same platform and used to capture images continuously. During image capture, the temperature of the camera was recorded by a thermal sensor.

Using the measured objective distance and the imaging distance (\(u = 650\) mm and \(v = 125\) mm), and camera parameter \(k_{\text{lens}}\) and \(k_{\text{CCD}}\) measured in section 2.2, the theoretical image expansion rate \(r_{\text{et}}\) can be calculated according to Eq. (7), and the relative image expansion \(\alpha_{\text{et}}\) during the whole experiment can be evaluated based on the measured camera temperature. On the other hand, by finding the coordinates of the corners of the chessboard images using a Harris detector [13] and then fitting them to a plane, the experimental relative image expansion \(\alpha_{\text{em}}\) can be obtained. The experiment was performed with three different imaging arrangements (as listed in Table 1), and for each arrangement the experiment was repeated three times. Figure 6(c) shows the measured and estimated relative image expansion, \(\alpha_{\text{em}}\) and \(\alpha_{\text{et}}\). The image expansion rate \(r_{\text{em}}\) evaluated by conducting the fitting and theoretical value \(r_{\text{et}}\) estimated by the model are listed in Table 1. The consistence of the measured value and the estimated value verifies the physical model of image expansion.

![Experiment to verify the physical model of temperature induced image expansion showing (a) the schematic of the experimental setup, (b) a photo of the experimental setup and (c) comparison between the measured and theoretical estimated relative image expansion for three different imaging arrangements: \(u = 460\) mm, \(v = 136\) mm for the left, \(u = 640\) mm, \(v = 126\) mm for the middle and \(u = 4000\) mm, \(v = 325\) mm for the right.](image)

| \(k_{\text{lens}}\) (\(\mu\text{m/}°\text{C}\)) | \(k_{\text{CCD}}\) (\(\mu\text{m/}°\text{C}\)) | \(u\) (mm) | \(v\) (mm) | \(r_{\text{et}}\) (\(\mu\text{m/}°\text{C}\)) | \(r_{\text{em}}\) (\(\mu\text{m/}°\text{C}\)) | Relative error (%) |
|---|---|---|---|---|---|---|
| 1 | 4.4 | 3.1 | 460 | 136 | 19.1 | 18.7 | 7.1 |
| 2 | 640 | 126 | 17.2 | 16.6 | 5.9 |
| 3 | 4000 | 325 | 5.1 | 4.9 | 4.4 |

It should be noted that the physical model above is constructed on the assumption that the imaging hardware is fixed on the platform by fixing the camera, not the lens. However, in...
some special circumstances, for example, when the lens is very large and heavy [14], the imaging system could be fixed by the lens. It is expected that the image expansion for this kind of imaging system is negative to the result from the model above.

2.4 Calibration of camera parameters $k_{CCD}$ and $k_{lens}$

It is shown in Eqs. (7) and (8) that, the estimation of self-heating induced image expansion is based on the imaging parameters ($u$ and $v$) and camera parameters ($k_{CCD}$ and $k_{lens}$). The imaging parameters can be easily measured or calibrated using the well-developed calibrated procedure [2]. However, the measurement for camera parameters, $k_{CCD}$ and $k_{lens}$, described in section 2.2 is too difficult for most users. Thus an easier calibration method is needed.

The experiment in section 2.3 indeed provides a method to calibrate the camera parameters: i) fixing the camera to be calibrated in the similar experimental arrangement as shown in Fig. 6, adjusting the target and lens, and then measuring (or calibrating) the imaging parameters ($u_1$ and $v_1$); ii) recording temperature and image data, processing the data to obtain the relationship between relative image expansion and temperature increasing, and then conducting data-fitting to obtain image expansion rate $r_{e1}$; iii) adjusting the target and lens to another imaging arrangement, measuring the imaging parameters ($u_2$ and $v_2$), repeating the data recording and processing in step (ii) to obtain $r_{e2}$. Finally, the two camera parameters are calculated as

$$
k_{lens} = \frac{u_1u_2(v_1r_{e1} - v_2r_{e2})}{u_2v_1 - v_2u_1},$$

$$k_{CCD} = \frac{u_1v_1(u_2 + v_2)r_{e1} - u_2v_2(u_1 + v_1)r_{e2}}{u_2v_1 - u_1v_2}. \quad (9)$$

If one of the two imaging arrangements (say the second one) is adjusted to be the telephoto optical path, the two parameters are then calculated as

$$
k_{lens} = u_1r_{e1} - \frac{u_1v_1}{v_1}r_{e2},$$

$$k_{CCD} = u_1r_{e1} - \frac{v_1(u_1 - v_1)}{v_1}r_{e2}, \quad (10)$$

where $v_\infty$ is the imaging distance corresponding to the telephoto optical path.

Using the calibrated method described above, the camera parameters of another two cameras used in this paper are calibrated and listed in Table 2.

| Camera type       | $k_{lens}$ ($\mu m^\circ C^{-1}$) | $k_{CCD}$ ($\mu m^\circ C^{-1}$) |
|-------------------|-----------------------------------|-----------------------------------|
| Imperx-16M3-L     | 4.4                               | 3.1                               |
| Basler A641F      | 2.1                               | 1.8                               |
| DH-1310FM         | 1.4                               | 1.1                               |

3. Self-heating induced error for different photomechanic methods

3.1 Strain and phase errors induced by image expansion

The analysis and experiments described in section 2 explains and verifies that an increase in the camera temperature will cause an image expansion. It is understandable that the image expansion will induce a virtual strain in image analysis based photomechanic methods, such as DIC. Obviously, the strain error should be equal to the relative image expansion, that is

$$
\varepsilon_{err} = \alpha_{e}. \quad (11)
$$
For fringe analysis methods, such as Michelson interferometry, the absolute phase value of a point can decrease because of image expansion (as shown in Fig. 7) and the relative phase error is calculated as

\[
\varphi_{\text{err}} = \varphi - \frac{1}{\alpha_i + 1} (\varphi - \varphi) = \alpha_i - \varphi,
\]

where \( \varphi \) is the original absolute phase value of a point. Equation (12) shows that the relative phase error is equal to the relative image expansion in magnitude but with the opposite sign.

Fig. 7. The phase error induced by image expansion showing (a) the original fringe image, (b) the expanded fringe image and (c) the corresponding phase value.

The above analysis indicates that the image expansion induced by the temperature variation of the digital camera will induce a measurement error for both kinds of photomechanic methods. The temperature induced error was experimentally verified for some typical photomechanic methods as described in the following sections.

3.2 Temperature induced strain error for image analysis based photomechanic methods; DIC as an example

The experimental arrangement used to measure the temperature induced strain error in the DIC method was the same as that described in section 2.3 except that the target was covered with speckles using spray paint, as shown in Fig. 8(a). The imaging system is also changed to a Basler A641f digital camera (CCD sensor with resolution of 1624 × 1236 pixels) and Avenir 12.5-75 mm lens, and the speckle image captured is shown in Fig. 8(b). After adjusting the camera and lens to obtaining clear image, the object distance and imaging distance are measured (\( u = 460 \) mm and \( v = 65 \) mm). The experiment was repeated three times and each experiment lasted for 2 hours.

Fig. 8. Experimental arrangement for the measurement of the camera self-heating induced strain error in DIC showing (a) the imaging target, (b) the captured speckle image and (c) the DIC analysis scheme.
Taking the first image as the reference image, the displacement fields corresponding to each subsequent image can be calculated using DIC. For each speckle image, the displacement of 48 points (as shown in Fig. 8(c)) were first calculated, then the average strain error in the $x$ directions were evaluated by fitting the displacement field using a first order polynomial. For the displacement field calculation, a sub-set of DIC of size $81 \times 81$ pixels was chosen and the Newton-Raphson and bi-cubic spline interpolation methods were used to obtain the sub-pixel displacement [15].

Strain in the $x$ directions is used to express the error $\varepsilon_{err}$. Figure 9 shows the relationship between the strain and the variation of camera temperature and, from the curve, a strong correlation between the strain error and camera temperature can be seen. The error strain rate (error strain per degree), which is equal to the image expansion rate ($r_e$) according to Eq. (11), can be fitted from the data as $9.0 \, \mu\varepsilon/\degree$, meaning that a one degree increase in temperature will induce about $9.0 \, \mu\varepsilon$ in DIC for the imaging system in this experiment. Using the measured $u$, $v$ value and the camera parameters in Table 2, the theoretical error strain rate is calculated and plotted on Fig. 9(b). The measured error is in consistence with the estimated error.

![Fig. 9](image.png)

**Fig. 9.** The camera self-heating induced strain error in the DIC method showing (a) the strain and temperature variation with the time, and (b) the linear relationship between strain and temperature.

The reason that the image expansion rate in this experiment is different from that in section 2.3 for similar imaging arrangement is due to the use of different imaging arrangements as well as different cameras. According to Eqs. (7) and (8), different camera parameters ($k_{CCD}$ and $k_{lens}$) will induce different image expansion rate for the same imaging arrangements. The differences of camera parameters for different cameras are mainly due to the differences on the structure and geometry of the camera cases and mounts, as shown in Fig. 10, as well as the differences on materials that manufacturing them.
3.3 Temperature induced strain error for fringe analysis based photomechanics methods; Michelson interferometry as an example

Michelson interferometry is a typical interferometry based photomechanic method, and the experimental setup to measure the temperature induced error for this is shown in Fig. 11. The DH-1310FM digital camera (CMOS sensor with resolution of 1280 × 1024 pixels, Avenir 12.5-75 mm lens) was used to capture the interference fringes, which represents the off-plane displacement of a reflective plate. After adjusting the camera and lens to obtaining clear image, the object distance and imaging distance are measured (u = 490 mm and v = 55 mm). A thermal sensor was bonded to the camera to measure the temperature during the experiment. The experiment was repeated three times, for each time the images were captured and saved every 3 minutes and the experiment lasted for a total of 2 hours. One of the captured fringe images is shown in Fig. 11(b), and the phase of the fringe has been analyzed by the Fourier Transformation method [16], with the wrapped and unwrapped phase maps are shown in Figs. 11(d) and (e) respectively. With the unwrapped phase map, the average relative phase error is evaluated by fitting the phase map using a first order polynomial.

The relative phase error, \( \phi_{err} \) against camera temperature is shown in Fig. 12. A relative strong correlation between the relative phase error and the camera temperature variation can be seen. The phase error rate (relative phase error per degree) is fitted from the data as \(-9.1 \times 10^{-6} \, \text{PC}^{-1}\), which indicates a relative image expansion rate of \(9.1 \times 10^{-6} \, \text{PC}^{-1}\) according to Eq. (12). The estimated phase error rate using the measured \(u, v\) value and the camera parameters in Table 2 is also plotted in Fig. 12(b). The measured error is in consistence with the estimated error considering the measurement noises during experiment.

Fig. 11. The experiment used to measure the camera self-heating induced phase error in Michelson interference method and the image data obtained by digital camera showing (a) photos of experiment arrangement, (b) the image obtained by the camera, (c) the region used for phase analysis, (d) the wrapped phase result, and (e) the unwrapped phase result.
The experiments in this section verify that the camera self-heating induced image expansion does bring in measurement errors for both types of photomechanic methods, namely the image-analysis-based or fringe-analysis-based method. For image analysis based photomechanic methods, the strain error is equal to the relative image expansion. For fringe analysis based photomechanic methods, the relative phase error is equal to the negative value of the relative image expansion. The consistence between the measured errors and the theoretically estimated errors further verified the model proposed in section 2.

4. Compensation of the self-heating induced error in photomechanics; DIC as an example

In order to compensate for the camera self-heating induced error, it must first be evaluated and then subtracted from the measured result. Two methods can be used to evaluate the error: First, the image expansion rate, which could be converted to strain error for image analysis based methods or relative phase error for fringe analysis based methods, of the imaging system is calibrated before the experiment and the camera temperature is recorded during the whole procedure. After the experiment, the temperature induced error is obtained from the product of the error strain rate (or the error phase rate) and the recorded camera temperature variation. This method is named the Temperature Recording Method (TRM). Secondly, an unloaded compensation specimen is placed in the same field of view, and at the same distance from the focus plane as the measured specimen. The measured result on the specimen could be directly regarded as the temperature induced error. This method is named as the Compensation Specimen Method (CSM).

An experiment was performed to verify the two compensation methods above. As shown in Fig. 13, two column shaped specimens made of low-carbon steel, with dimensions of $10 \times 10 \times 20$ mm$^3$, and placed on the loading flatten of a WDW-50 test machine. The surface of each specimen was painted with a speckle pattern. During the experiment, specimen A was compressed with a load speed of 0.005 mm/min while specimen B remained unloaded, and the camera temperature was recorded using a thermal sensor. An Imperx-16M3-L camera with a Sigma macro 105 mm F2.8DG lens was used to capture the speckle image from both specimens with a speed of 1fps. Before the experiment, the error strain rate of the system was calibrated as $15.4 \times 10^{-6}$ C$^{-1}$. Strain gauges are used as a standard for comparing with the DIC method.
Then the strain $\varepsilon_y$ (in loading direction) was corrected by TRM and CSM respectively. The strain correction results are shown in Fig. 14(a). It is seen that the uncorrected DIC result has a quite large deviation from that of the strain gauge, but the corrected DIC results are in good consistence with that of strain gauge. The evaluation results of the elastic modulus using the measured and corrected strain are shown in Fig. 14(b). It can be seen that the elastic modulus (288.7 GPa) evaluated using the uncorrected DIC result has a large deviation from the result of strain gauge (223.6 GPa). However, the elastic modulus evaluated using the corrected strain, 241.6 GPa for TRM and 221.5 GPa for CSM, are more accurate (as listed in Table 3).

It can also be seen that the compensation result for CSM is better than that for TRM. This is reasonable as TRM only uses an average error strain rate to cover the entire heating stage, but the CSM records the error during the whole heating stage. However, TRM is easier to realize than CSM because the compensation specimen is not needed. In some experiments, this is very important because the pixel resolution of the image can be greatly decreased if an extra specimen were to be placed in the field of view.

| Strain gauge value | Not corrected | Corrected by TRM | Corrected by CSM |
|--------------------|---------------|------------------|------------------|
| Elastic modulus (GPa) | 223.6 | 288.7 | 241.6 | 221.5 |
| Deviation from the result of strain gauge (%) | / | 29.1 | 8.1 | 0.9 |
5. Conclusion

The systematic error of photomechanics caused by temperature variation of a digital camera induced by self-heating was systematically studied. The self-heating of the camera causes notable camera temperature variations during long periods of image recording. The camera temperature increase induces a corresponding image expansion with a rate of around 10 $\mu$ε°C$^{-1}$, depending on the imaging system used. A model to explain the image expansion was constructed and verified, indicating that camera structures ($k_{CCD}$ and $k_{lens}$) and the imaging parameters ($u$ and $v$) control the image expansion rate.

Camera self-heating induced image expansion will cause an equivalent strain error in image analysis based photomechanic methods, and an equivalent but negative relative phase error to fringe analysis based photomechanic methods. For photomechanic methods, the DIC method and Michelson interferometry were tested and the temperature induced error was verified. For a 10 degree temperature increase, which is typical for most of experiments, the strain or relative phase error can be in the order of $100 \times 10^{-6}$~$200 \times 10^{-6}$, which is large enough to interfere with measurements and should be compensated. Two compensation techniques were proposed, which subtract the evaluated error from the original measured result. For the Temperature Recording Method (TRM), the error is evaluated by calibrating the image expansion rate of the imaging system before the experiment and then recording the temperature variation during experiment. For the Compensation Specimen Method (CSM), the error is evaluated by using an unloaded specimen in the same view and at the same distance as the measured specimen.

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