Experimental Study on the Effect of Medium in Optical Path on Digital Image Correlation Measurement

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Abstract. To explore the effect of optical media on digital image correlation measurement, the experiments of digital image correlation measurement under different optical media conditions were carried out. By analyzing the speckle images non-special optical path medium, common ordinary glass medium and quartz glass medium in the optical path, the effect of medium change in the optical path on digital image correlation measurement is discussed. The results show that the effect of different optical media on the accuracy of digital image correlation measurement is different, and the effect of optical media on absolute displacement measurement is much greater than that of rigid body displacement measurement. The effect of optical medium on different measuring areas is also different. The effect of quartz glass state on strain measurement is greater than that of ordinary glass. The effect of optical medium on the measurement of vertical optical axis displacement is much less than that of optical axis displacement measurement. Whether ordinary glass or quartz glass is added, the measurement error of camera optical axis direction is much larger than that of vertical optical axis direction; the stability of DIC displacement measurement in different optical path media is in turn ordinary glass medium, quartz glass medium and non-special optical path medium.

1. Introduction
With the rapid development of optoelectronic technology and computer, a series of modern optoelectronic experimental mechanics methods with high accuracy, non-contact and non-damage, such as electronic speckle interferometry, phase-shift method, time series method, etc., are gradually moving towards digitalization and automation [1]. Digital image correlation (DIC) has attracted much attention due to its characteristics of full-field measurement, low requirement for light source and measurement environment, and has been widely used in scientific research and engineering measurement [2]. Digital image correlation (DIC) has attracted much attention due to its characteristics of full-field measurement, low requirement for light source and measurement environment, and has been widely used in scientific research and engineering measurement. As a measurement tool, digital image correlation method is affected by many factors, such as image quality, optical lens distortion, mirror distortion and search algorithm [3-7]. However, most of the researches...
focus on how to eliminate the effect by changing the calibration algorithm. These often need to ensure that the whole measurement process is consistent with the initial state of the calibration. In some cases, due to the variability of the state, it is difficult to modify it by a specific calibration method. Therefore, the whole process state of envelope analysis has great engineering application value and significance for DIC measurement. Based on this, this paper carries out experimental research on digital image correlation measurement under different optical path media conditions. By analyzing speckle images collected under three conditions: no special optical path media, ordinary glass and quartz glass, the effect of medium change in optical path on digital image correlation deformation measurement is discussed.

2. Effect principle of optical path on of digital image correlation

From the optical point of view, after adding glass to the optical path measured by CCD camera, as shown in Figure 1, the optical path is offset due to the refraction of light, and the offset is the X indicated in the figure. According to Snell’s law, the relationship is as follows:

\[
\frac{\sin a}{\sin b} = \frac{n_b}{n_a}
\]

(1)

Among them, \(\alpha\) and \(\beta\) are the incident angle and refractive angle of light passing through glass, \(n_a\) and \(n_b\) are the absolute refractive index of air and glass respectively, and the relative refractive index can be expressed as:

\[
n_r = \frac{n_b}{n_a}
\]

(2)

The geometric relationship between incident angle and refraction angle can be expressed as follows:

\[
\Delta x = 2t \left( \frac{x}{L} - \frac{x}{\sqrt{L^2 + x^2}} \right) \left( \frac{L}{L - 2t} \right)
\]

(3)

Among them, it is the thickness of glass, \(L\) is the distance from the camera to the specimen, and \(n_r\) is the relative refractive index. From the optical point of view, the optical offset is related to the thickness of glass, the refractive index and the distance between the camera and the specimen. In digital image correlation measurement, when the distance between the measured object and the camera and the thickness of the glass are constant, the effect of the glass on DIC measurement depends mainly on the refractive index produced by different optical paths.

In order to explore the effect of optical media on digital image correlation measurement, the experimental design of different optical media on DIC measurement was carried out, as shown in Figure 2. The purpose of the vibration isolation platform in the figure is to reduce the errors caused by environmental vibration. Fixed the test piece, CCD camera and glass plate fixture on the vibration isolation platform, replaced the glass through glass fixture, and adjusted the optical path medium. According to the above experimental scheme, the DIC measurement state is designed based on three working conditions: no special optical path medium, ordinary glass medium and quartz glass medium. Among them, the length, width and thickness of quartz glass are 375mm × 375mm × 5mm, the
transmittance is 92%, and that of ordinary glass is 375mm x 375mm x 5mm, and the transmittance is 80%. Before the start of the experiment, the CCD camera was preheated for 5 hours to reduce the effect of the error caused by the camera's own heat dissipation on the measurement accuracy. The random speckle fabrication and the installation of the experimental testing system were carried out on the specimen surface (300mm x 300mm). The internal and external parameters of the measuring system were calibrated by the special calibration board for DIC measurement. After that, direct measurement of the glass-free state of the test piece relative to the static measurement system is started. After the measurement is finished, the ordinary glass is placed on the fixture of glass. After fixing, the test piece is measured under the ordinary glass condition. After the measurement, the ordinary glass is replaced by quartz glass, and the specimen is measured after installation. 10 sets of data were measured under different working conditions. In order to make the data result more reliable, this paper intercepts two position areas as shown in Figure 3 for data calculation, and stipulates that the optical axis direction of the camera is Z axis, and the displacement components perpendicular to the optical axis direction of the camera are X axis and Y axis, respectively.

3. Results and discussion
In order to explore the effect of optical media on digital image correlation measurement, Figure 4 shows the in-plane displacement measurement results of specimens without special optical media, ordinary glass and quartz glass. Among them, the abscissa is the number of image sequences, and the ordinate represents the average in-plane displacement DMS in all directions. The first ten sets of data in the figure are the measurement results without special optical path medium, the middle ten groups are the test results after adding ordinary glass in the middle, and the last ten groups are the test results after adding quartz glass. In the figure, Circle 1 and circle 2 are measured in two sampling areas (the same below). Figure 4 shows that the in-plane displacement of the component of the optical axis direction of the camera and the optical axis direction of the vertical camera is close to zero (less than 2 micron) in the absence of a special optical path medium. This shows that calibration and measurement without special optical medium is the fluctuation of displacement caused by environmental change. When ordinary glass medium is added, the in-plane displacement measurement results vary greatly due to glass refraction. Table 1 shows the specific numerical changes. After adding ordinary glass, the in-plane displacement of the optical axis component X direction of the vertical camera is 24.12μm and 12.3μm, respectively. After adding quartz glass, the in-plane displacements in the X direction are 1.215μm and 1.6μm, respectively. It can be seen that for the X direction component of the optical axis of the vertical camera, adding quartz glass has little effect on the measurement results, which is similar to the measurement results without special optical path medium. When adding ordinary glass in the
middle, the measurement value of X direction displacement reaches 24.6 μm, which is much larger than that without special optical path medium and quartz glass. For the Y direction of the optical axis component of the vertical camera, the maximum in-plane displacement in the Y direction is 93.4μm after adding ordinary glass, while the maximum in-plane displacement in the Y direction is 8.6μm after adding quartz glass. Under three working conditions, the displacement measurement results of the optical axis direction (Z direction) of the camera show that after adding glass medium to the measuring optical path, whether ordinary glass or quartz glass is added, the error of Z direction measurement is far greater than that of X direction and Y direction, the maximum is 1814.22 μm, and the error of quartz glass working condition is slightly smaller than that of ordinary glass working condition. Therefore, it is obtained that for the measurement of optical axis displacement of vertical camera, compared with the state without special medium. The introduction of quartz glass into the measuring optical path will not bring about greater measurement error, but the introduction of ordinary glass will bring about greater measurement error. When glass medium is added to the optical path, the measurement error of the optical axis direction of the camera is much larger than that perpendicular to the optical axis, whether ordinary glass or quartz glass is added.

Table 1. Displacement variation of region /μm.

| Region | Direction | Glassless/μm | Ordinary glass/μm | Quartz glass/μm |
|--------|-----------|--------------|-------------------|-----------------|
| 1      | X         | -0.50        | -24.62            | 0.715           |
|        | Y         | 0.40         | 76.30             | -9.70           |
|        | Z         | -0.85        | 1812.2            | 1787.68         |
| 2      | X         | -0.66        | -11.64            | -2.26           |
|        | Y         | -0.45        | 93.70             | -6.40           |
|        | Z         | -1.99        | 1814.22           | 1783.31         |

Figure 4. In-plane displacement of specimens in different optical paths.

Figure 5. De-rigid displacement of specimens in different optical paths.

Figure 5 shows the measurement results of de-rigid body displacement without special optical path medium, ordinary glass medium and quartz glass medium. Among them, the abscissa is the number of image sequences, and the ordinate represents the de-rigid body displacement in all directions. It can be clearly seen from the figure that de-rigid body displacement in the optical axis direction and the vertical optical axis direction of the two cameras in the absence of special optical path medium is close to 0. After adding different glass medium, the change trend is different. For the vertical component of
the camera optical axis (X direction), the displacement of the de-rigid body increases with the addition of ordinary glass, reaching a maximum of 7μm, while the displacement of the de-rigid body decreases to 4μm with the addition of quartz glass. The de-rigid body displacement measurement value of the Y direction component of the optical axis of the vertical camera decreases to 5μm after adding ordinary glass, and increases to 1μm after adding quartz glass. For the Z direction of the optical axis of the camera, the measured value of the de-rigid body displacement increases or decreases after adding ordinary glass or quartz, and the measured value of the de-rigid body displacement in area 1 is quite different from that in area 2. The system error is eliminated as much as possible during the experiment, but there will be random error. So the change trend of the Z direction of the camera optical axis to de-rigid body is not consistent with other directions. At the same time, it can be clearly seen that the effect of optical path medium on absolute displacement measurement is much greater than that of de-rigid body displacement measurement.

Figure 6 shows the principal strain measurements of the measured area under different optical paths. Figure 6(a) and (b) show the principal strain measurements of region 1 and region 2, respectively. As can be seen from the figure, the first principal strain measurement value for region 1 is basically zero in the absence of special optical path medium. The change of principal strain is obvious after adding different glass materials. Among them, after adding ordinary glass, the measured value of principal strain is slightly larger than that under the condition of no special optical path medium. After adding quartz glass, the measured value of principal strain is larger than that under the condition of ordinary glass. Generally speaking, the effect of optical medium on strain measurement is greater than that of ordinary glass.

Figure 7 gives the standard deviations of DIC measurement in different optical media perpendicular to the optical axis direction component X, Y and Z of the camera. It can be seen from the figure that the standard deviation in the direction of X and Y perpendicular to the optical axis of the camera is in the order of ordinary glass medium, quartz glass medium and no special optical path medium. The standard deviation in Z direction of the optical axis of the camera in ordinary glass medium is basically the same as that in quartz glass medium, but the standard deviation in three directions is the smallest without special optical medium (i.e. the minimum degree of dispersion of the measured results). According to the comparison of standard deviation of DIC measurement results in different optical path media, the order of standard deviation is ordinary glass medium, quartz glass...
medium and no special optical path medium, which indicates that the measurement results of DIC in the absence of special optical path medium are stable.

4. Conclusion
In this paper, experimental research on DIC measurement under different optical path media is carried out. By analyzing speckle images collected under three conditions: no special optical path media, ordinary glass and quartz glass, the effect of medium change in optical path on digital image correlation deformation measurement is discussed. The following conclusions are drawn.

1) Optical medium has significant effect on displacement and strain measurement of DIC system. Generally speaking, the effect of optical medium on absolute displacement measurement is much greater than that of rigid body displacement measurement. The effect of optical medium on different measuring areas is also different. The effect of quartz glass state is greater than that of glass state.

2) The effect of optical medium on displacement measurement in different directions is different. For the measurement of optical axis displacement of vertical camera, the introduction of quartz glass into the optical path will not bring larger measurement error than that without special medium, and the introduction of ordinary glass will bring larger measurement error. When glass medium is added to the optical path, the measurement error of the optical axis direction of the camera is much larger than that perpendicular to the optical axis, whether ordinary glass or quartz glass is added.

3) Comparing the standard deviation of DIC displacement measurement results under different optical path media, the order of standard deviation from large to small is ordinary glass medium, quartz glass medium and no special optical path medium. The degree of dispersion of DIC measurement results without special optical path medium is the smallest, and the measurement results are more stable.

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