Exploring of PST-TBPM in Monitoring Dynamic Deformation of Steel Structure in Vibration

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Abstract. In order to monitor the dynamic deformation of steel structure in the real-time, digital photography is used in this paper. Firstly, the grid method is used correct the distortion of digital camera. Then the digital cameras are used to capture the initial and experimental images of steel structure to obtain its relative deformation. PST-TBPM (photographing scale transformation-time baseline parallax method) is used to eliminate the parallax error and convert the pixel change value of deformation points into the actual displacement value. In order to visualize the deformation trend of steel structure, the deformation curves are drawn based on the deformation value of deformation points. Results show that the average accuracy and relative accuracy of PST-TBPM are 0.28mm and 1.1‰, respectively. Digital photography used in this study can meet accuracy requirements of steel structure deformation monitoring. It also can warn the safety of steel structure and provide data support for managers' safety decisions based on the deformation curves on site.

1. Introduction

Steel structures are characterized by its evenly material, high working reliability, high strength, light weight, good plasticity and toughness, strong ability to resist shock and vibration [1]. Steel structures therefore are applied in many engineering structures. Steel structures develop a large deformation and plastic damage occurs when the force exceeds the capacity of the steel structure. In some cases, steel structures develop brittle damage suddenly without large deformation signs. Thus, it is very important to monitor dynamic deformation of completed steel structures or steel structures in construction and to warn their safety in real time.

However, traditional surveying methods, such as the level instrument and the total station, cannot monitor the dynamic deformation over time [2]. Such task is technically possible for a physical sensor, which is however practically challenging due to its limited application for local deformation and vulnerability in direct contact with the target. GPS (Global Positioning System) [3, 4] is restricted to monitor small amplitude swing deformation. The three-dimensional laser scanning [5] cannot capture...
instantaneous deformation of deformation points either. These problems can be solved by applying
digital photography.

Digital photography [6, 7] consists of photogrammetric survey and information technology. It uses
a non-metric digital camera [8-10] to monitor multiple points and to capture the instantaneous
deforation of a deformable object. It therefore presents an opportunity to monitor the dynamic
deforation of engineering structures [11]. In this study, PST-TBPM (photographing scale
transformation-time baseline parallax method) is proposed to explore its feasibility in the digital
photography.

The aim of this study is to monitor the dynamic deformation of a steel frame by PST-TBPM and to
analyse the measurement accuracy of PST-TBPM.

2. Digital photography

2.1. Correcting distortion of digital cameras

This paper used a grid method [12] to eliminate the distortion of the digital camera to improve its
measurement accuracy. Figure 1 shows the grid (50cm×50cm) used in the experiment. Figure 2 shows
the feature Point moving from A to A’ affected by the distortion.

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Figure 1. Grid Figure 2. Analysis of grid error

After eliminating the distortion, we assess the measurement accuracy of the digital camera [13].
Table 1 shows that the measurement accuracy is at the range of 0 to 1 millimeter, and the relative
accuracy reaches 2‰.

| Point number | Calculated distance /mm | Measured distance /mm | Difference /mm |
|--------------|-------------------------|-----------------------|----------------|
| U0-U2        | 588                     | 589                   | 1              |
| U1-U3        | 596                     | 595                   | 1              |
| U2-U4        | 599                     | 599                   | 0              |

2.2. Photographing scale transformation-time baseline parallax method

The time baseline parallax method is commonly used to solve digital camera data [13]. But it consists
of the parallax caused by the camera vibrating [14]. For improving the measurement accuracy, the
PST-TBPM (Figure 3) was used to correct errors caused by the change of intrinsic and extrinsic
parameters of digital cameras. And the photographing direction is perpendicular to the reference plane
and the object plane, respectively. The reference plane does not coincide with the object plane.

In this method, when a point on an object moves from A to B (Figure 3), ΔX and ΔZ are:
Where $M$ is the photographing scale on the reference plane, $\Delta X$ and $\Delta Z$ are the horizontal and vertical deformation of deformation point on the object plane, $\Delta P_x$ and $\Delta P_z$ are the horizontal and vertical displacement of deformation point on the image plane, $SA$ and $Sa$ are the photographic distance and the focus respectively.

Figure 3. Photographing scale transformation- time baseline parallax method

Reference plane in Figure 3 consists of six reference points labeled as C0-C5. It is used to match images and eliminate the parallax.

Thus, we obtained the deformations based on the photographing scale $M$:

\[
\begin{align*}
\Delta X_R &= \frac{SA}{Sa} \Delta P_x = M \Delta P_x \\
\Delta Z_R &= \frac{SA}{Sa} \Delta P_z = M \Delta P_z
\end{align*}
\]

Where $(\Delta P_x', \Delta P_z')$ are the corrected displacements of the deformation point on the image plane. $\Delta X_R$ and $\Delta Z_R$ are the horizontal and vertical deformation of deformation point on the reference plane.

Then, the actual deformations are obtained by the coefficient of the photographic scale transformation:

\[
\begin{align*}
\Delta X' &= \Delta is \cdot \Delta X_R \\
\Delta Z' &= \Delta is \cdot \Delta Z_R
\end{align*}
\]

Where $\Delta is$ is the coefficient of the photographic scale transformation, $(\Delta X', \Delta Z')$ are the corrected actual deformations of the deformation point on the object plane.

If $\Delta is$ was 1, the reference plane would coincide with the object plane.
3. Steel structure impact experiment

3.1. Steel frame
As is shown in Figure 4, steel frame consists of the beams (30mm×30mm×3mm) and upright beams (30mm×30mm×3mm). A hanger was welded on its corner to suspend the shock. Furthermore, circle targets (35mm in diameter) are attached to the steel frame as deformation points. A circle target was divided into four parts. The two sides of the diagonal are sprayed black in order to find the center point.

Figure 4. Steel frame

3.2. Experimental process
Figure 5 shows the experiment site. Firstly, digital cameras were used to take a image of the steel frame without any impact on it, as the reference image. Then, a rope was used to connect the dumbbell with the hanger. A 7-kg dumbbell was dragged to create a 20-degree, 40-degree, 60-degree and 75-degree angle between the rope and the vertical direction respectively. Loosen the dumbbell to hit the steel frame. A 10.2-kg dumbbell was dragged to create a 20-degree, 40-degree, 60-degree and 75-degree angle between the rope and the vertical direction respectively. Loosen the dumbbell to hit the steel frame. A 14.5-kg dumbbell was dragged to create a 20-degree, 40-degree, 60-degree and 75-degree angle between the rope and the vertical direction respectively. Loosen the dumbbell to hit the steel frame. What is more, we make steel frame develop plastic damage through applying a force to the dumbbell to hit steel frame at a 75-degree angle between the rope and the vertical direction. We used digital cameras to monitor every impact moment and got 13 images. Table 2 shows the impact loads.

Table 2. Impact loads

| Dumbbell weight /kg | Angle between the rope and the vertical direction/(°) |
|---------------------|------------------------------------------------------|
| 7                   | 20 40 60 75                                          |
| 10.2                | 20 40 60 75                                          |
| 14.5                | 40 50 60 75                                          |

4. Experimental data and discussion
After eliminating random noise and the parallax, we can obtain the measurement accuracy of PST-TBPM in monitoring the dynamic deformation of steel structure. As is shown in Table 3, the average absolute accuracy and relative accuracy are 0.28mm and 1.1‰, respectively. Relative accuracy is equal to the ratio of the absolute accuracy to the actual length. Thus, PST-TBPM used in this study can meet measurement accuracy of steel structure deformation monitoring.
Table 3. Measurement accuracy

| Line No. | Actual length/mm | Measured length/mm | Absolute accuracy/mm | Relative accuracy |
|----------|------------------|--------------------|----------------------|------------------|
| U2-U3    | 296.8            | 296.9              | 0.1                  | 0.34‰           |
| U3-U4    | 278.8            | 278.6              | 0.2                  | 0.72‰           |
| C2-C3    | 241.4            | 241.2              | 0.2                  | 0.83‰           |
| C6-C7    | 253.9            | 253.3              | 0.6                  | 2.4‰            |
| C7-C8    | 225.1            | 225.4              | 0.3                  | 1.3‰            |
| Average  |                  |                    | 0.28                 | 1.1‰            |

Then, the actual relative deformations are obtained through using the photographic scale to multiply relative pixel displacement on image plane. The dx7 and dz7 in Table 4 represent the relative deformation of deformation point U7 in x and z direction respectively. The others in Table 4 are in a similar fashion.

This study draws instantaneous deformation curves of deformation points U7, U8, U11, U12 and U13 based on deformation data in Table 4. According to Figure 6, we can find that these deformation points except U8 move around a vertical axis. This represents a good flexibility of steel frame. As U8 is located on the impact position, large deformation occurs on it. These phenomena are consistent with deformation law of steel structure.

![Instantaneous deformation curves of steel structure](image)

Figure 6. Instantaneous deformation curves of steel structure

Table 4. Actual relative deformation (/mm)

| Period | dx7 | dz7 | dx8   | dz8   | dx11  | dz11  | dx12  | dz12  | dx13  | dz13  |
|--------|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|
| 1      | 0.26| -0.09| 0.23  | -0.79 | -0.68 | 0.26  | -0.73 | -0.42 | 0.96  | -0.27 |
| 2      | -0.32| -1.16| -0.31 | -0.83 | 0.57  | 0.38  | 0.58  | 0.74  | 0.59  | 1.03  |
| 3      | 0.47 | -1.7 | 0.48  | -0.23 | -1.24 | 0.42  | 0.49  | 0.49  | 1.08  | 0.5   |
| 4      | -0.49| -1.21| 1.25  | -2.32 | -0.46 | 1.77  | 1.27  | 1.57  | 1.29  | 1.25  |
| 5      | 0.19 | -0.46| -5.3  | -0.25 | 0.4   | 0.84  | 0.05  | 1.07  | -1.1  | 0.4   |
| 6      | -0.82| -1.3 | 1.2   | -0.75 | 1.51  | 0.69  | 0.96  | 2.15  | 0.36  | 1.77  |
| 7      | -1.93| -1.37| -0.09 | -2.06 | 0.03  | -0.16 | 0.15  | 0.89  | 0.24  | 1.04  |
| 8      | -0.57| -1.03| -0.04 | -2.24 | -1.24 | 0.01  | -0.74 | 1.42  | -1.03 | 1.87  |
| 9      | -0.86| -1.19| -0.1  | -1.61 | -0.2  | 0.57  | -0.31 | 1.05  | -0.4  | 0.57  |
| 10     | 0.56 | -2.1 | 5.18  | -1.79 | 4.63  | 0.27  | 1.5   | -0.25 | 0.9   | 0.88  |
| 11     | -0.72| -1.95| 1.2   | -1.39 | 0.53  | -0.79 | -0.14 | 0.69  | -0.84 | 1.19  |
| 12     | 0.07 | -2.54| 2.95  | -1.77 | 1.04  | 0.75  | -0.72 | 0.72  | 0.4   | 1.4   |
| 13     | 0.36 | -2.82| 5.36  | -1.46 | 1.75  | -0.07 | 0.71  | -0.39 | 0.57  | 0.05  |
Note that the instantaneous deformation curves of steel frame were only based on the instantaneous deformation at the time of the dumbbell impacting the steel frame. If high speed cameras were used to continuously monitor the whole impact process, it would provide more data to analyze the performance of steel frame.

5. Conclusion
In this study, PST-TBPM is explored to monitor the dynamic deformation of a steel frame. Through processing the images, the conclusions are as follows:

(1) PST-TBPM improves the measurement accuracy. The average absolute accuracy and relative accuracy are 0.28mm and 1.1‰, respectively.

(2) Digital photography used in this study can simultaneously monitor instantaneous and dynamic deformation of multiple deformation points and draw their deformation curves in real time.

(3) The deformation trend curves can warn the safety of steel structure.

Digital photography used in this study provides technical support for managers' safety decisions on site. It can also be used to monitor the dynamic and instantaneous deformation of other engineering structures. If high speed cameras were used to continuously monitor the deformation process, it would provide more data to analyze the performance of deformation object.

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