Research on Dynamic Structure Displacement Monitoring Based on Feature Optical Flow Method

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Abstract: In view of the difficulty of sensor installation and complicated process in traditional structure health monitoring, a feature point monitoring based on optical flow is proposed in this paper. A high-speed camera is applied to capture the dynamic response of the structure under excitation, and feature point could be selected and marked at any position in the video. The movement of the selected point could be traced and calculated by feature optical flow method, and the displacement time series of the feature point could be obtained. Results show that the displacement time series obtained from proposed method in this paper is consistent with the data of the pull-wire displacement sensor, the maximum displacement error is 3.3%, the method proposed is more flexible, convenient and of low cost.

1. Introduction

High-rise buildings and long-span structures play a very important role in ensuring people’s safe and the development of national economy. Up to 2019, the total number of modern bridges in China exceeds 1 million, at the same time, the number of in-service bridges in China’s highway entering the maintenance period is increasing, more than 100,000 bridges are in unsafe condition. In the case of these dangerous bridges on alert, diverse dynamic loads, including traffic, wind, and earthquakes can aggravate the condition of the structures. Therefore, it is necessary to monitor and evaluate the condition of the bridge structure to ensure them in safety condition. The corresponding characteristics of dynamic displacement are the most intuitive performance of bridge, and it is also one of the most vital parameters for judging the health of the bridge⁵.

In traditional monitoring methods, the dynamic responses of the structure is obtained by sensors installed in structure or on the surface. Abdel-Ghaffer and Scanlan⁶ applied specially deployed and oriented motion-sensing accelerometers to monitor the Golden Gate Bridge, and environmental vibration under wind and earthquake conditions is utilised to determine the effective damping, three-dimensionality modal shape and vibration frequency. Results are in good accordance with the numerical
results of two-dimensional and three-dimensional model. 13 acceleration sensors are installed on the 111-meter bridge superstructure and columns by Soyoz and Feng [3], and they monitored the bridge for 5 years, obtained the probability density function of the bridge stiffness, and determined the bridge collapsed stiffness threshold. Asadollahi and Li [4] applied a dense array of wireless smart sensor networks with 113 smart sensors installed on a cable-stayed bridge in South Korea to record ambient acceleration. The data collected by sensors were used for comprehensive statistical analysis such as natural frequencies, modal damping and mode shapes of the bridge, and the results have a high resolution and confidence in identified modal properties.

Huge height and volume of structures monitored result in extra difficulties in sensor installation, which is deteriorated by complex environments or surroundings like complicated wiring and heavy traffic, as a result non-contact measurement are a better choice. With the development of digital image, signal processing and computer technology, various structural displacement monitoring methods based on video-image technology continue to appear and have been verified in actual projects. Dong [5] proposed a non-contact structural dynamic characteristics identification method based on machine vision technology, and verified the feasibility of this method in experiments. An advanced template matching algorithm based on a vision sensor system for remote measurement of structural displacements was developed by Feng [6], satisfactory agreements are observed between the displacements measured by the single camera and those measured by high-performance laser displacement sensors. Ye [7] combed the research and progress of the structural displacement monitoring method based on computer vision, introduced the template matching method, feature point matching method, full-field optical flow method, sparse optical flow method, geometric matching method, particle image velocimetry (PIV), color matching method, and target tracking method based on deep learning. Eight target tracking methods, analyzed the advantages and disadvantages of various methods and gave suggestions for target tracking.

Based on that, this paper achieved the precise extraction of any feature points of interest, applied the Lucas-Kanade [8] optical flow method to calculate the displacement, and developed a set of displacement measurement programs based on machine vision. This method and pull-wire displacement sensor were used in the laboratory to test the transformer, which verified the feasibility of the algorithm developed in displacement monitoring in this paper.

2. Theory and process of feature based structure dynamic displacement tracking

2.1 Optical flow calculation corner motion algorithm

The main algorithm principle in the calculation of feature point displacement is based on the difference method of LUCAS - KANADE optical flow estimation, and follows two basic assumptions:

1. The gray intensity of the moving object remains unchanged in a short interval;
2. The velocity vector field in a given neighborhood changes slowly.

As shown in Figure 1, suppose the pixel intensity of the tracking target in the video at time $t$ is:

\[ I(x, y, t) \]

After time $\Delta t$, the point has a slight displacement, and its intensity is represented by $I(x + \Delta x, y + \Delta y, t + \Delta t)$. According to the assumption 1 of the optical flow method:

\[ I(x, y, t) = I(x + \Delta x, y + \Delta y, t + \Delta t) \]

(1)

Expand the right end of equation (1) using a first-order Taylor series as:

\[ I(x + \Delta x, y + \Delta y, t + \Delta t) = I(x, y, t) + \frac{\partial I}{\partial x} \Delta x + \frac{\partial I}{\partial y} \Delta y + \frac{\partial I}{\partial t} \Delta t \]

(2)

Substituting formula (2) into formula (1) to sort out:

\[ \frac{\partial I}{\partial x} \Delta x + \frac{\partial I}{\partial y} \Delta y + \frac{\partial I}{\partial t} \Delta t = 0 \]

(3)

which is:

\[ I_{x} u_{x} + I_{y} u_{y} + I_{t} = 0 \]

(4)

Where: $I_{x} = \frac{\partial I}{\partial x}$, $I_{y} = \frac{\partial I}{\partial y}$, $u_{x} = \frac{\Delta x}{\Delta t}$, $u_{y} = \frac{\Delta y}{\Delta t}$, $I_{t} = \frac{\Delta I}{\Delta t}$.
In the same way, it can be known that I-1, I-2, I-3, I-4, I-6, I-7, I-8, and I-9 around the marked pixels in Figure 1 can also list the same formula.

| Pixel $I_{(x,y,t)}$ | I-6 |
|--------------------|-----|
| I-1                |     |
| I-2                |     |
| I-3                |     |
| I-4                |     |
| I-7                | I-8 |
| I-9                |     |

Figure 1. Calculate adjacent pixel motion

Combining all the formulas, as shown in formula (5), it can be solved by the least square method.

$$
\begin{bmatrix}
    I_{1x} & I_{1y} \\
    I_{2x} & I_{2y} \\
    \vdots & \vdots \\
    I_{9x} & I_{9y}
\end{bmatrix}
\begin{bmatrix}
    u_x \\
    u_y
\end{bmatrix}
= 
\begin{bmatrix}
    I_{t1} \\
    I_{t2} \\
    \vdots \\
    I_{t9}
\end{bmatrix}
$$

(5)

2.2 Shi-Tomasi feature corner

A corner point is a point that is more prominent and has obvious changes in each direction and the gray information is used to make judgments in the detection of image key points. This article uses the Shi-Tomasi[9] corner point algorithm, which is an improved version of the Harris[10] corner point algorithm. In many cases, it can get better results than the Harris corner point algorithm. In this paper, a memory algorithm is added after the corner parameter setting is completed, so that the program can memorize the initially selected corner parameters, and stably recognize the initially selected characteristic corners in the subsequent tracking process.

2.3 Calibration

Mark two points arbitrarily on the first frame of the two-dimensional image sequence, calculate the pixel distance between the two points as $D_p$, and input the actual distance $D_r$ of the world coordinates. The coefficient $\alpha$ is the ratio of the actual distance to the pixel distance, As shown in formula (6), and use this scale factor as the calibration parameter of all images taken by the device at the spatial position.

$$
\alpha = \frac{D_r}{D_p}
$$

(6)

In the formula, $\alpha$ is the calibration coefficient

The structural dynamic characteristics recognition method proposed in this paper is mainly to track the pixels in the image, determine the position of the selected pixel in each frame, and convert the obtained pixel displacement to the actual physical length to finally achieve monitoring. First use the camera to shoot the excitation process of the structure, then select the feature points in the two-dimensional image sequence, and then calibrate on the picture, and finally start the program to track the feature point, the program will automatically calculate the data and output the movement of the feature point, the specific process is shown in Figure 2.
3 Structural dynamic displacement tracking experiment, analysis and verification

3.1 Experimental overview
To verify the feasibility of the above method, seismic experiment of a power transformer were carried with shake table as follows, to measure, analyse, and validate the dynamic displacement response of structures, by monitoring a feature point on top of transformer with proposed method. Figure 3 shows a transformer with a height of 14.08m, which is rigidly connected by five ceramic cylinders with a diameter of 1.13m and a length of 2.18m. The bottom is 0.5m high and fixed to the vibration table. The parameters of the high-speed camera and mobile phone are shown in Table 1. The shooting direction is orthogonal to the axis of the transformer, and the distance from the transformer is 17m. The pull-wire sensor in Figure 4 is arranged on the top of the structure to measure the horizontal displacement of the top; the dynamic acquisition instrument (DEWE2-A4) is used to obtain the dynamic response information of the transformer structure, and the acquisition frequency is 500 Hz. The sensor parameters are shown in Table 2. The overall spatial location diagram is shown in Figure 5.

![Figure 3. Transformer test](image)

| Camera     | Fps  | Resolution    |
|------------|------|---------------|
| FDR-AX700  | 50fps| 1920*1080     |
| Iphone 8 plus | 30fps| 1920*1080     |

Table 1 Camera parameters
Figure 4. Pull-wire displacement sensor

Table 2 NS - WY06 pull-wire sensor parameters

| Specifications      | Technique data |
|---------------------|----------------|
| Precision           | 0.1%           |
| Measuring range     | 1200mm         |
| Non-linear error    | ≤0.5%          |
| Output              | 0~10V          |
| Displacement speed  | ≤0.7m/s        |

Figure 5. Schematic diagram of transformer test

Excitation is applied through the bottom vibrating table, traditional measurement and video shooting are started before the excitation is generated and the experimental data of continuous response is recorded until it stops.

As shown in Figure 6, the distance between the two flanges is $D_f = 420$mm, the pixel distance is $D_p = 43$ pixel, and the final scale factor is $\alpha = 9.76$ pixel, which is expressed as 1 pixel $= 9.76$ mm.
3.2 Analysis of results

This section compares the actual measurement results with the program calculation results to verify the feasibility of the program. Figure 7 is the traditional measurement method using the pull-wire displacement sensor (500Hz) to measure the displacement time history curve of the top of the transformer, Figure 8 (FDR-AX700, 50fps, 1920*1080) and Figure 9 (Iphone 8 plus, 30fps, 1920*1080) is the time history curve of the top displacement of the transformer after processing the captured video using the developed characteristic optical flow method.

![Diagram of transformer with points A and B labeled with coordinates (462,513) and (462,556), and an aluminum circular pipe labeled as well.]

Figure 6. Pixel and actual distance calibration

![Graph showing displacement time history with pull-wire displacement sensor data.]

Figure 7. Displacement time curve by pull-wire sensor
As shown in Figure 10, the video taken at a distance of 17m from the test object using two devices at the same resolution and different frame rate, the results obtained have the same line shape, the gap is very small, the higher the frame rate, the more data and the smoother the curve, and the maximum error of the displacement value is 1.6%.

The frequency of the sensor sampling frequency is 500Hz, and the video frame rate of the shooting is 30fps and 50fps respectively. After the processing is completed, a section of the data(0-3s) obtained by the cable displacement sensor data and the characteristic optical flow measurement is intercepted and placed in Figure 11 for analysis. It can be seen that the two measurement results are very consistent, and the maximum error of the displacement value is 3.3%, indicating that the characteristic optical flow
method can meet the requirements in the structural displacement measurement.

![Comparison of traditional measurement and camera captured results](image)

**Figure 11.** Comparison of traditional measurement and camera captured results

### 4. Conclusion

This paper proposes a new non-contact structural dynamic displacement detection method based on feature point and optical flow theory, and has achieved the target point tracking and the acquisition of the history diagram of the point in structures. By dynamic displacement analysis of a transformer in vibration experiments, comparing with traditional detection methods, the following conclusions are obtained:

1. The method proposed in this paper can select any feature point on the structure and obtain the displacement data of this point, which solves the cumbersome problem of the traditional displacement measurement method.

2. The results obtained from long-distance shooting at different frame rates, after using the method proposed in this article, the error of the same point displacement data result is up to 1.6%.

3. The displacement calculation result obtained by using the method proposed in this paper is very consistent with the displacement time history curve of the result obtained by the traditional measurement method. The maximum error of the displacement value is 3.3%, which can meet the detection requirements.

4. The method in this article is very adaptable. In the whole test process, the displacement can be detected directly without adding any artificial marks to the structure.

The method proposed in this paper uses ordinary civilian shooting equipment for video capture, and lacks industrial-grade high-resolution, high frame rate video and the ability to detect in extreme environments needs further testing and verification.

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