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Vibration Detection for Mobile Phone Based on Digital Image Correlation Method

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Abstract: *To solve the problem of vibration test of mobile phone, a non-contact testing method is proposed based on binocular stereo vision. The method determines the internal parameters of the lens and the external parameters of two industrial cameras by camera calibration. After obtaining the corresponding region between the two cameras by digital image correlation matching, the point coordinates of three-dimensional space are reconstructed based on laser triangulation method, and the vibration of a point with the same name is calculated by tracking its three-dimensional position in adjacent frames. The method has the advantages of non-contact and full-field measurement. The experimental results show that the proposed method has high accuracy. Compared with the measurement results of the vibrometer, the maximum deviation of the proposed method is 0.04 mm and the average deviation is 0.021mm. The proposed method can measure the vibration direction and amplitude of the designated area on the mobile phone, which provides a test method for the verification and optimization of mobile phone vibration technology.*

Keywords: *Mobile phone; Vibration test; Digital image correlation method; Random speckle; binocular stereo vision*

1. Introduction

Vibration is a necessary function of modern smart phones, and it is generated by the rotation of eccentric wheels in the vibration motor. The direction and amplitude of mobile phone vibration are affected by the design of the motor, rotational speed, installation position, etc [1], these factors together determine the vibration comfort [2]. The vibration testing technology is very important to optimize the engineering design of vibration comfort and improve the user experience.

To obtain the better user experience and mobile phone performance, the optimal mobile phone vibration mode was obtained to reduce the influence on human body and mobile phone energy consumption through modeling and finite element simulation [3]. However, it is difficult to obtain the vibration value of each point on the mobile phone surface. In the actual vibration test, the acceleration sensor was used to test the vibration amount at the designated position of the mobile phone [4]. This method has the disadvantages of contact measurement, the test location may be limited, and the mutation location was missed. The digital image correlation technology [5-7] was usually used for deformation measurement, and it is a reliable and accurate non-contact full-field deformation measurement method. Based on its characteristic of tracking homonymous points, this method is to measure the vibration of rigid body. The full-field test capability of method can effectively solve the problems of limited test positions and missing vibration mutation.

The correlation function is used to calculate the local region correlation of the front and rear frame images to achieve the matching of the corresponding regions in the front and rear frame images. this method is used for deformation region matching, such as material deformation measurement [8], particle image velocimetry [9], motion tracking based on optical flow method [10] and other applications.

A non-contact mobile phone vibration test method is proposed based on binocular stereo vision technology and digital image correlation technology in this paper. The internal parameters, external parameters and distortion coefficient of stereo vision system is obtained based on Zhang Zhengyou calibration method [11], and the digital image correlation technology is used to match the speckle image subarea [12], calculate the three-dimensional coordinates of pixel points based on parallax [13], and calculate the vibration amount of the mobile phone by comparing the coordinate values of adjacent images, which can quickly and conveniently calculate the vibration direction and amplitude of the

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phone in the whole field. In this paper, the test objects are vibration, which is essentially a rigid body movement without material deformation. Therefore, local region matching based on digital image correlation method will be more robust.

2. Random speckle generation

Speckle is a kind of artificial texture pattern, random and scattered texture features are helpful for digital image correlation method to match the gray value of local scattered patches, which is better than the lack of such texture features on the front and back of the mobile phone. Therefore, unique speckle patterns need to be designed and sprayed on the surface of the mobile phone through the mold to form features of uniform thickness and black and white dots. In this paper, the number of speckles is specified in the rectangular area, and the speckle position and gray value are generated randomly, thus obtaining the speckle image, as shown in Figure 1. The speckle map was obtained by the simulation method in literature [11], the location of speckle was calculated according to Formula 1, and the gray value of each speckle was calculated combined with Formula 2.

$$\begin{cases} X = \max X \times rand\left(X\right) \\ Y = \max Y \times rand\left(Y\right) \end{cases} \tag{1}$$

Where, $\max X$ and $\max Y$ represent the number of pixels in the U and V directions of the speckle pattern, and $rand\left(X\right)$ represent a random number between 0-1.

$$I = I_0 \times \frac{\pi}{4} \times s^2 \times \sum \left[\begin{array}{l} \left(erf\left(\frac{i - X\left(i\right)}{a}\right) - erf\left(\frac{i + 1 - X\left(i\right)}{a}\right) \right) \\ \times \left(erf\left(\frac{j - Y\left(j\right)}{a}\right) - erf\left(\frac{j + 1 - Y\left(j\right)}{a}\right) \right) \end{array} \right] \tag{2}$$

Where, I_0 refers to the peak intensity of speckle, it is set as 7; a indicates the size of the speckle, it is set 5;

$$erf(x) = \frac{2}{\pi} \int_0^x e^{-\varepsilon^2} d\varepsilon \tag{3}$$

Due to the vibration test is conducted in this paper, the test object will not be deformed. Speckle stickers can be printed and pasted on the surface of the mobile phone for vibration test. The thickness of speckle stickers is only about 0.02mm, which will not affect the vibration characteristics and test results of the test location.

Figure 1: Speckle pattern

3. Image correlation matching

The matching principle of the digital image correlation method is shown in Figure 2, and the left image is the reference image. Take the center of the subarea (x, y) of the rectangular image as the matching point, according to the correlation function, the subregion with the maximum correlation coefficient with the reference subregion is queried in the matched image, the central point of the

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subregion is (x', y'). Thus, image pixel correlation matching can be realized.

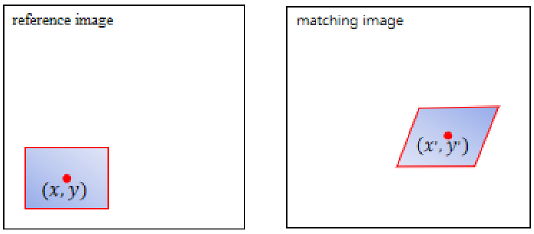

Figure 2: Schematic diagram of digital image correlation method

3.1 Speckle grid division

In order to carry out local area speckle matching, it is necessary to mesh the entire speckle area, generate image blocks, and divide the speckle area into grids of the same size. The uniform division method is adopted in the paper, and the rectangular grid is divided equally according to the side length a, b. The horizontal and vertical division times of the speckle are as follows:

$$m = W / a$$

$$n = H / b$$

Then the number of grids s=m×n. Number the grid from left to right and from top to bottom, ID=1, 2, 3, ... , s. The divided grid is shown in Figure 3.

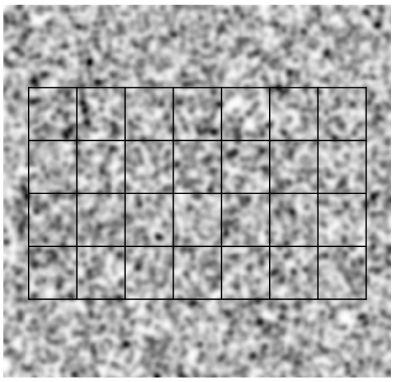

Figure 3: Grid Generation

3.2 Correlation matching

Correlation matching is to calculate the similarity of two speckle grids based on the correlation function and match the most relevant grid patterns. If the matching is successful, the spatial points can be reconstructed based on the three-dimensional reconstruction principle.

3.2.1 Mapping function

The image coordinate of a point P in the image is $P(x, y)$, and the corresponding point P' in the image coordinate after vibration is (x', y'). Since the test object does not deform, only rigid body motion occurs, the mapping relationship between the two points is a zero-order mapping function:

$$\begin{cases} x_i^{'} = x_i + u \\ y_i^{'} = y_i + v \end{cases}$$

Where: u represents the pixel displacement in the direction of x; v indicates the pixel displacement of the direction y.

3.2.2 Correlation measurement

Correlation refers to the similarity between the gray distribution of the pixels contained in each sub-grid in the image and the sub-grid in other images. In this paper, correlation is represented by correlation coefficient. The larger the correlation coefficient is, the stronger the correlation is. Since the test object in this paper does not deform, the gray level of each subgrid does not change. In addition, the vibration range is limited, generally less than 2mm, so it is not necessary to consider the influence of the uneven illumination of the image, while the correction of illumination is required in the more complex deformation measurement [13]. Considering the convenience of the solution, it is not necessary to use complex correlation functions for correlation evaluation. In this paper, the Sum of Squared Differences (SSD) is used.

$$C_{SSD}(p)=\sum_{i=1}^{m}\sum_{j=1}^{n}\left[f(x_i,y_i)-g(x_i^{'},y_f^{'})\right]^2$$

According to formula (1),

$$C_{SSD}(p)=\sum_{i=1}^{m}\sum_{j=1}^{n}\left[f(x_i,y_i)-g(x_i+u,y_f+v)\right]^2 \tag{4}$$

Where, $f(x,y)$ the gray value of any point in the reference sub-image, $g(x+u,y+v)$ is the gray value of the corresponding point $P^{'}$ of the point in the deformed image.

3.2.3 Image sub-region correlation matching

The speckle is divided into several sub-areas for matching. The purpose of sub-area matching is to find the corresponding grid area on the image during the vibration process and to match the pixel blocks. For the two images taken by the binocular camera, the purpose of the corresponding region matching is to carry out the three-dimensional reconstruction of the pixel points and obtain the three-dimensional spatial coordinates of the pixel points. For the two cameras of the binocular system, the motion tracking of the pixel block is realized after the image sequence taken by each camera is matched with the adjacent frame image. Combined with the above class matching method, the three-dimensional coordinates of pixel points are reconstructed, and the coordinate points are tracked in real time to obtain vibration information.

In the process of matching the corresponding sub-region of the image in the three-dimensional reconstruction of binocular stereo vision, the polar correction is performed according to the calibration results to reduce the matching search space. According to the sub-region selected on the left camera image, the SGBM algorithm is used to match the corresponding sub-region on the right camera image. This method is mature and will not be repeated in this paper.

For the matching of the corresponding points on the adjacent frame images in the image sequence, in order to reduce the matching search space, this paper adopts the seed point search method [12]. The method assumes the displacement of the adjacent grid is continuous. If the seed point is matched successfully, then the seed point can be used as the initial value. The matching search of the adjacent grid only needs to be carried out in the adjacent sub-area of the seed point, thus greatly reducing the search range. First of all, divide the speckle area into grids, and select the grid in the middle as the seed point. Then, calculate the correlation minimum of the grid to be matched according to the correlation function to obtain the whole pixel displacement, and then use the quadratic surface fitting algorithm to perform sub-pixel interpolation [14-15]. For the grid with the pixel size (3, 4 or 5), an equation $n\times n$ can be listed, and the coefficient of the surface can be solved based on the minimum quadratic multiplication method. After obtaining the coefficient of the surface function, the position of the sub-pixel point of the fitting function can be obtained [8].

$$C(x_i,y_j)=a_0+a_1x_i+a_2y_j+a_3x_i^{2}+a_4x_iy_j+a_5y_j^{2}$$

$$\frac{\partial C(x_i,y_j)}{\partial x_i}=0$$

$$\frac{\partial C(x_i,y_j)}{\partial y_j}=0$$

After the seed point is matched, according to the distance between the seed point and its adjacent

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point on the left camera image, the initial value of the position of the adjacent point on the image to be matched can be calculated through the mapping function, which is usually very close to its actual position. After the four neighboring grids are successfully matched by using the seed points, these four neighboring grids can be used as seed points to provide the initial values of relevant parameters for other grids, and continue to spread outward until all grids are matched.

4. Vibration calculation

After the text gets the corresponding point, it can calculate the parallax to get the depth value of the point, thus the completing three-dimensional of the pixel point is reconstructed.

$$D = f \times b / d \,.$$

$$d = (x_l - x_r) - (c_{xr} - c_{xl})$$

$$d = (x_l - x_r) - (c_{xr} - c_{xl})$$

Where, D represents the depth value of the pixel, f represents the focal length of the camera, b represents the baseline distance of the binocular system, d represents the parallax, xl and xr represents the pixel value of the corresponding point direction under the left camera coordinate system and the right camera coordinate system respectively. cxr indicates the main point deviation x of the right camera direction and cxl is the main point deviation of the left camera direction.

Then the coordinate of the spatial 3D point corresponding to the pixel point is

$$\begin{cases} X = (x - c_x) \times b / d \\ Y = (\mathrm{y} - c_y) \times b / d \\ Z = D \end{cases}$$

After obtaining the three-dimensional coordinates of pixel points, the direction $\vec{V}$ and amplitude A of vibration are calculated according to the corresponding points matched in the adjacent frame images as follows:

$$\vec{V} = P_1 - P_0 \,.$$

$$A = \| \vec{V} \| \,.$$

5. Algorithm flow

The algorithm flow of vibration calculation is shown in Figure 4.

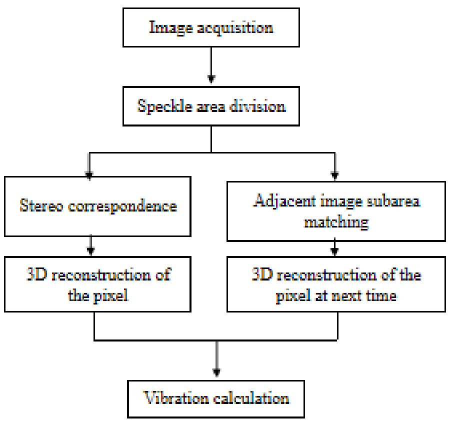

Figure 4: The algorithm for mobile phone vibration test

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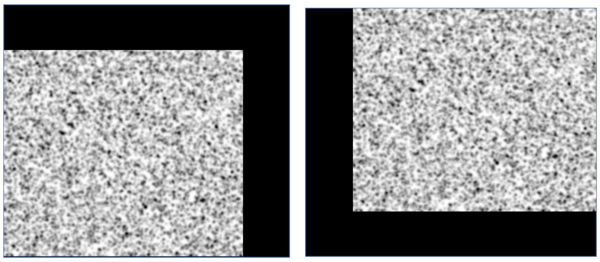
6. Experiment and analysis

The algorithm test platform in this paper is Lenovo Y7000 notebook computer, the CPU is Intel i5-11400H processor, the main frequency is 2.7GHz, and 16G memory.

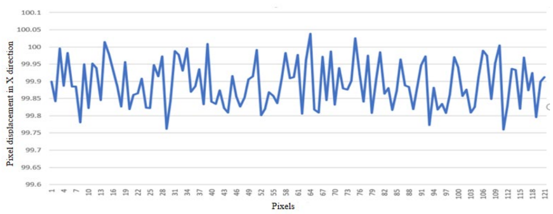
6.1 Simulation test

By simulating two speckle images with known displacement (as shown in Figure 5), the known matching image moves pixels relative to the reference image, and the matching accuracy of the image sub-region is tested by the above matching method. Set the side length of grid division to 25 × 25, sliding step is set to 9×9, tested 15×15 pixel points. Since all the pixel points on the matched speckle are in translation motion, the displacement standard value of the tested pixel points is x=100, y=100. The displacement values of the matched pixels in the X and Y directions are shown in Figure 6.

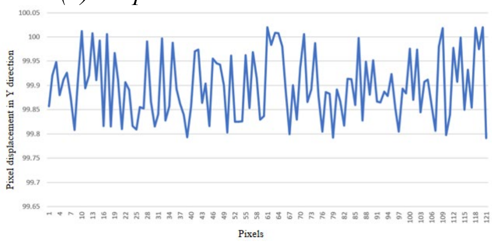


(a)Reference image *(b) Match image*

Figure 5: Analog digital speckle



(a) Displacement in the X direction



(b) Displacement in the Y direction

Figure 6: Simulation test results of displacement

The statistical displacement deviation is shown in Table 1. The average deviation of X and Y direction matching is 0.125 pixels and 0.103 pixels respectively, and the standard deviation is 0.101 pixels and 0.095 pixels respectively, indicating that the speckle sub-region matching algorithm proposed in this paper has high accuracy, which ensures the accuracy of speckle image displacement calculation, and provides a basis for accurate vibration measurement.

Table 1: Displacement deviation of simulation experiments

Direction	Minimum Deviation(Pixel)	Maximum Deviation(Pixel)	Mean Deviation(Pixel)	Standard Deviation(Pixel)
X Direction	0.008	0.236	0.125	0.101
Y Direction	0.005	0.212	0.103	0.095

6.2 Vibration test

In this paper, the ZED 2i stereo camera is used to collect speckle images, and the parameter image resolution is 1344×376. Acquisition frame rate: 100FPS. Paste the speckle map sticker designed above

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on the back of the phone, as shown in Figure 7.

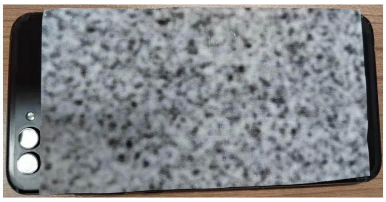

Figure 7: Speckle pattern sticker

After collecting the image, select a rectangular area on the speckle image to mesh, and calculate the vibration displacement field on the mobile phone speckle. According to the binocular system, the three-dimensional coordinate points of pixel points are reconstructed, and the corresponding displacement values are calculated, and the displacement values are mapped to the corresponding color values for thermal map display. The generated displacement field is shown in Figure 8. From this figure, it can be seen that the position marked by the red rectangular box in the thermal map is the position with the strongest amplitude, and the maximum amplitude is close to 0.6mm. This position is the installation position of the mobile phone vibration motor. The farther away from this position, the smaller the amplitude is, the amplitude at the farthest point is about 0.3 mm.

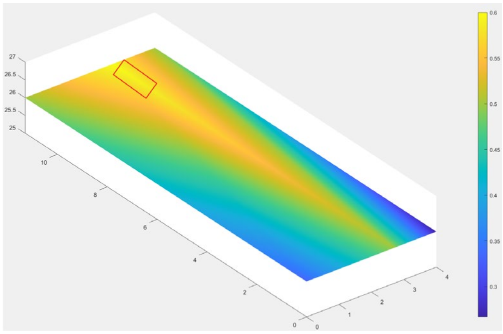

Figure 8: Vibration displacement field of mobile phone

The amplitude of a single pixel position is tracked in the test, and the measurement of the amplitude of a single pixel point is more of engineering significance. By adjusting the vibration mode of the mobile phone, such as alarm, call reminder, SMS reminder and other vibration modes, this method measures the amplitude change curve of a single point at a certain position of the mobile phone under the alarm mode, as shown in Figure 9. From the figure, we can see that the actual vibration amplitude increases gradually from small, then decreases gradually, and then increases gradually, the maximum amplitude is about 0.56mm and the minimum amplitude is about 0mm. The fitting curve of the measured data is shown in the red part of the figure. The fitting curve conforms to the trend of the sine curve, which is similar to the vibration sense when the alarm bell vibrates.

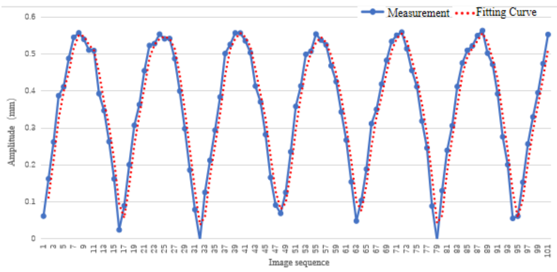

Figure 9: Single point vibration amplitude of mobile phone

7. Comparison test

In order to further show the effectiveness of the test method in this paper, the vibration meter is used to test the amplitude of some discrete points on the mobile phone (as shown in Figure 10), and the results are compared with the test results of this method to verify the effectiveness of this method. The amplitude measurement range is 0.001-1.999mm and the measurement frequency is 10Hz-1KHz.

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Figure 10: The vibration meter for mobile phone vibration test

The test results of the vibration meter and the method in this paper are shown in Figure 11. The maximum deviation is 0.04 mm and the average deviation is 0.021 mm in 20 groups of experiments. According to the figure below, the test results of the method in this paper are relatively close to the test results of the vibration meter, indicating that the test method in this paper is effective and can achieve high-precision testing of mobile phone vibration.

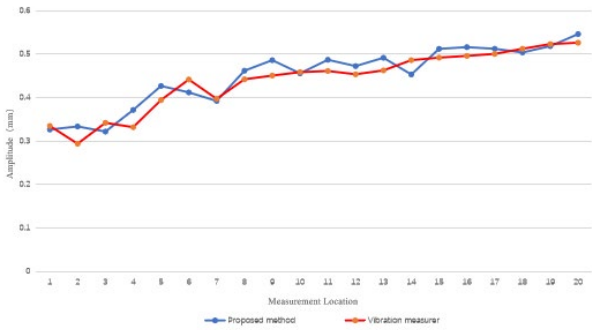

Figure 11: The test results comparison between our method and vibration meter

8. Conclusion

In this paper, digital image correlation method is applied to mobile phone vibration measurement by using binocular stereo vision technology and random speckle pattern.

1) Since deformation is not involved in vibration measurement, the zero-order mapping function is adopted in this paper, which reduces the computational complexity.

2) The sub-region matching of speckle image is completed by combining the seed point search method; Then, motion tracking and three-dimensional reconstruction are performed on the pixel points, and the vibration direction and amplitude are calculated. Compared with the measurement results of the vibration meter, the maximum deviation measured by the method in this paper is 0.04 mm, and the average deviation is 0.021 mm.

3) The effectiveness of this method is demonstrated by the combination of simulation experiment and actual measurement. The amplitude range of mobile phone vibration in a certain state is 0.3mm-0.6mm through the actual test, and the amplitude change curve at the single point position is obtained.

4) In order to further illustrate the accuracy of the test results in this paper, the test results are compared with the vibration meter. The average error of the two methods is 0.021mm, which shows the accuracy of the test results in this paper. The test method in this paper can realize the high-precision test of mobile phone vibration, and provides a full-field test method for the verification of mobile phone vibration design.

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