STUDY ON LASER SPECKLE CORRELATION METHOD APPLIED IN TRIANGULATION DISPLACEMENT MEASUREMENT

© 2013 г. **L. Shen*, D. G. Li*, F. Luo****

* Huazhong University of Science and Technology, Wuhan, PR China

** China Academy of Engineering Physics, Mianyang, PR China

E-mail: lidinggen@sina.com

Laser speckle is a kind of noise in triangulation displacement measurement. It's meaningless to restrain speckles when the imaging light spot is so weak that facular image cannot be extracted from speckles. Speckles can also be viewed as a kind of information carrier of displacement of the interface. In this paper, digital correlation method was used in laser triangulation displacement measurement system to measure the displacement of rough surface with strong scattering and the experimental results were analyzed. The results show that the digital correlation method is feasible in triangulation displacement measurement system, the measuring range can reach micron grade and the experimental errors are below 2% . This method can overcome the disadvantage of traditional laser triangular displacement measurement in rough surface with strong scattering, improve the accuracy and expand the scope of application.

Key words: *laser triangulation, displacement measurement, laser speckle, correlation method.*

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1. Introduction

Laser triangulation displacement sensor is an important tool in non-contact displacement measurement; it is widely used in the measurement of 3D contour, thickness, width, position, and vibration. It uses diffuse reflection light as sensor signal, which is formed by laser scattering on object surface. The diffuse reflection light is converged to a light receiver on the focal plane by lens imaging principle, and then the image point is formed on the receiver. The receiver can be charge coupled device (CCD), or position sensitive device. The object moving or surface changing leads to the shooting spot of incident light moving along the optical axis, and the image point on the receiver moves correspondingly. The displacement of objects, or the vibration amplitude and frequency can be determined according to the size of phase shifting and structural parameters of the sensor. The principle of laser displacement sensor is shown in fig. 1.

Take the direct-style triangulation method as an example, its light path is shown in fig. 1. In order to improve the accuracy, the scattering angle θ and the angle between CCD and normal plane of the lens φ must meet Scheimpflug [1] principle, in which the image plane, object plane and lens plane must intersect in a straight line, namely

$$\tan\theta = \beta \tan\varphi. \tag{1}$$

In formula (1), β is the lateral magnification. Based on the triangle similarity principle, the relation between actual displacement of object Δ and the displacement of image point δ is

$$\Delta = \frac{l \sin\varphi\delta}{l' \sin\theta \pm \delta \sin(\theta + \varphi)}. \tag{2}$$

If the measured surface moves down from the reference position, it's "–" in this formula, otherwise, it's "+". And in formula (2), l is the distance between lens and incident light spot on the object, l' is the distance between lens and image spot on CCD.

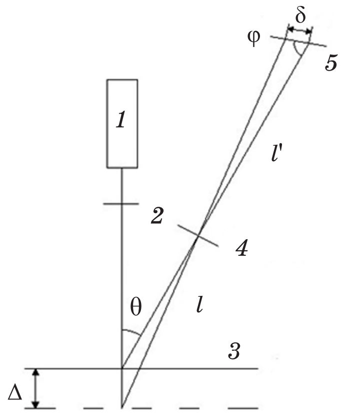


Fig. 1. Principle of Laser Displacement Sensor. *1* – laser, *2* – convergent lens, *3* – interface, *4* – imaging lens, *5* – CCD.

In terms of using the laser triangulation method stated above to measure the surface displacement, the following two aspects should be considered: the weak and strong scattering conditions. In the weak scattering condition, researchers always firstly use hardware filter and filtering software to make the signals smoothly, and by the center of gravity method one can get the change of gravity center of the signals before and after the displacement of object surface, namely the displacement of the light spot on CCD, and then the actual displacement value can be obtained. But when the object surface is rough and in strong scattering condition, the energy of speckle noise is so strong that the useful signal received by CCD cannot be extracted from speckle noise. Then it is useless to take measures to restrain speckles. This paper attempts to apply the digital speckle correlation method in triangular measurement to calculate spot displacement, this method can effectively utilize the function that speckle can reflect the information of measured surface structure. Digital speckle correlation method used in triangulation system with strong scattering situation will help to improve the accuracy of the displacement measurement of the light spot on CCD, thus improve the accuracy of actual displacement of measured object surface.

2. Theory

When a rough interface is shined by coherent waves, there will be a speckle field in the space because of the interference between the refraction waves and the back-scattered waves. Speckles can be viewed as a kind of noise, which affects the quality of image and leads to signal distortion, whereas it can also be viewed as an information carrier of the characteristics of the interface. When the interface moves, the space speckles change correspondingly, so this kind of speckle image may be applied in the object surface displacement measurement.

In recent years, the continuous development of electronic speckle pattern interferometry is widely used in the measurement of in-plane object surface displacement, the out-of-plane displacement, strain, vibration mode and other aspects [2, 3]. However, most of the displacement measurement methods above are based on the analysis, processing and calculation of speckle interference stripes which formed before and after the displacement of interface. This kind of measurement methods is difficult to implement in the laser triangulation displacement measurement which is based on single point test. This is because the laser triangulation method is for point measurement, not for area measurement, it cannot form interference stripes. However, the speckle correlation method without any interference stripes can obtain accurate displacement information with doing correlation processing on the speckle signals CCD received before and after the displacement.

In triangulation method measurement, for the situation of interface with low roughness and weak scattering, first step is to design the system hardware, namely the imaging system and the preamplifier filter function; then conduct digital filtering and smoothing, eliminating random errors in the data, and then research the application of median filtering method [4–6], finally calculate the exact location of CCD image point by the center of gravity method. This method of measurement needs a suppression to speckle effect, which can improve the accuracy of measurement. The formula of square weighted centroid method is as follows:

$$\bar{x} = \sum_{i=n_1}^{n_2} x_i f^2(x_i) \Bigg/ \sum_{i=n_1}^{n_2} f^2(x_i) \,. \qquad (3)$$

In formula (3), $\bar{x}$ is the abscissa of the center of gravity of received signal, x_i are the abscissas of all image elements, $f(x_i)$ are their ordinates, namely the light intensity value each image element received. Then one can obtain the moving distance of light spot on CCD:

$$d = \overline{x_2} - \overline{x_1}. \quad (4)$$

x_1, x_2 are the abscissas of the centers of gravity of the signals before and after the displacement. As shown in fig. 2, the signal CCD received in the situation of weak scattering is a triangle with a narrow apex angle, it satisfies the application range of the center of gravity method.

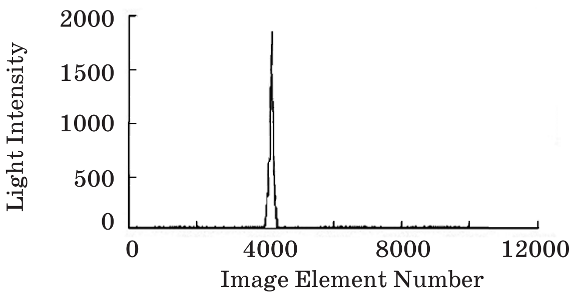


Fig. 2. Signal with Weak Scattering.

For the rough interfaces with strong scattering, the energy of speckle noise is so strong that the useful signal received by CCD cannot be extracted from speckle noise. Then it will have little significance to take measures to restrain speckles, at this time the center of gravity method will be no longer precise. Then researchers can turn to use the advantage of the speckles. When the interface moves, the speckles in the scattering space will also change with it. Accordingly, the surface displacement can be worked out by measuring out the speckle displacement correspondingly. In triangulation displacement measurement, the speckle intensity received by each pixel on CCD can be transfer into a digital matrix, when the speckle pattern moves along the CCD pixel array direction, the distribution of this one-dimensional digital matrix is almost the same, but the corresponding space coordinate of each pixel has been changed. One can truncate the one-dimensional digital matrix CCD received before the displacement of interface by a certain width window function, get the data which can reflect the information of scattering interface (for example, 300 pixels around the peak of the signal) as the sample interval, and then look for the same width interval (1–300, 2–301, 3–302, ... , 10251–10550) in the digital matrix after displacement of interface using correlation method. Use the one-dimensional digital correlation operation to search the intervals, and supplemented by interpolation, when search to the interval with maximum correlation coefficient, the speckle displacement can be obtained. This method is rapid and the result is accurate in sub-pixel level. The signal of strong scattering is not as smooth as the one in situation of weak scattering, as shown in fig. 3. However, in the context of weak scattering condition, as the quantity of speckle particles is less, effective pixels in the array will miss and it is not appropriate to use the correlation method.

Fig. 3 shows that the signal received by CCD from rough interface with strong scattering is mixed and disorderly and it has a long bandwidth, at this time the center of gravity method will be no longer precise. But it is consistent with the application range of the correlation algorithm.

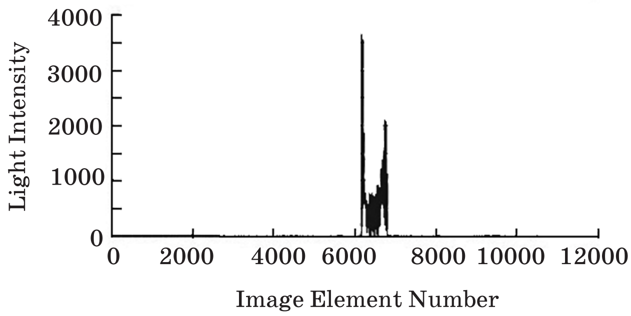


Fig 3. Signal with Strong Scattering.

There are a variety of formulas for digital correlation algorithm. This paper used one-dimensional standardization covariance correlation function formula in the data processing of triangulation displacement measurement with strong scattering interface:

$$C = \frac{\sum_{i=1}^{m}[f(x_i)-\overline{f}][g(x_i')-\overline{g}]}{\sqrt{\sum_{i=1}^{m}\left[f(x_i)-\overline{f}\right]^2}\sqrt{\sum_{i=1}^{m}\left[g(x'_i)-\overline{g}\right]^2}}. \quad (5)$$

In formula (5), $f(x_i)$ denote the elements of sample sub interval, namely the one-dimensional digital matrix which was truncated in the speckle signal received by CCD before displacement, $g(x_i)$ denote the elements of object sub interval, namely the matrix truncated in the signal after displacement. And m is the total quantity of the image elements truncated in the speckle signal.

$$x_i' = x_i + u \text{ and } \bar{f} = \sum_{i=1}^{m} f(x_i) \Big/ m,\ \bar{g} = \sum_{i=1}^{m} g(x'_i) \Big/ m$$

the value range of the correlation coefficient C is [−1, 1]. When the two matrices are completely consistent, the correlation coefficient was 1; when full of inconsistencies, the correlation coefficient was 0; when quite the opposite, the correlation coefficient was −1. With the correlation operation, when the correlation coefficient C reaching the maximum value, the calculated result is the displacement value of light spot on CCD.

Therefore, as the signals have narrow bandwidths with weak scattering interfaces and wide ones with strong scattering interfaces, this paper used center of gravity method in data processing when the bandwidth was narrow and used the digital correlation method when the bandwidth was wide.

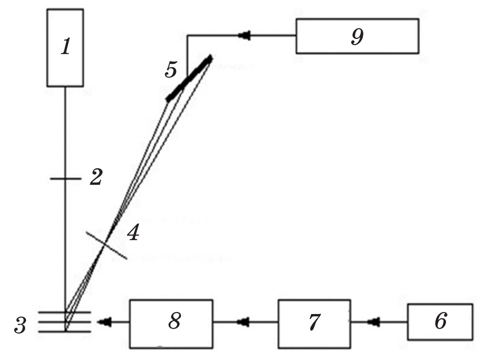
3. Composition of the sensor

3.1. Experimental system

Light path and actual device of laser triangulation displacement measurement are shown in fig. 4. The laser emits light, the light is focused by the convergent lens, and it shines on the interface straightly, the movement of the interface or surface change leads to the movement of the incident light spot along the optical axis. The imaging lens receives the scattering light, and images the light on the sensitive area of position detector (CCD) of light spot. Processing the data received by CCD before and after the displacement can get the displacement of light spot on the CCD, and then obtain the precise actual surface displacement.

In the diagrams (fig. 4), the translation stage is controlled by the stepping motor; its precision can reach micron level, and its displacement values will be compared with the results of correlation method to detect the accuracy and effectiveness of correlation method.

(a)



(b)

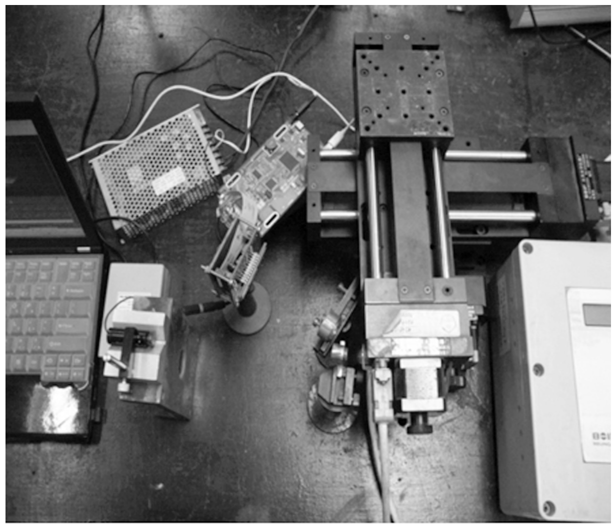


Fig. 4. Optical Path (a). *1* – laser, *2* – convergent lens, *3* – interface, *4* – imaging lens, *5* – CCD, *6* – computer, *7* – stepping motor, *8* – translation stage, *9* – control circuit. Actual Device (b).

3.2. Parameter setting

The influence of various optical parameters on the imaging effect in laser triangulation displacement measurement should be taken into consideration. The parameters of the optical devices interact with each other and all of them determine the imaging effect and the magnification of displacement. Magnification of displacement can be obtained from formula (2)

$$\frac{d\delta}{d\Delta} = \frac{ll'\sin\theta\sin\varphi}{\left[l'\sin\varphi \pm \Delta\sin(\varphi+\theta)\right]^2}. \qquad (6)$$

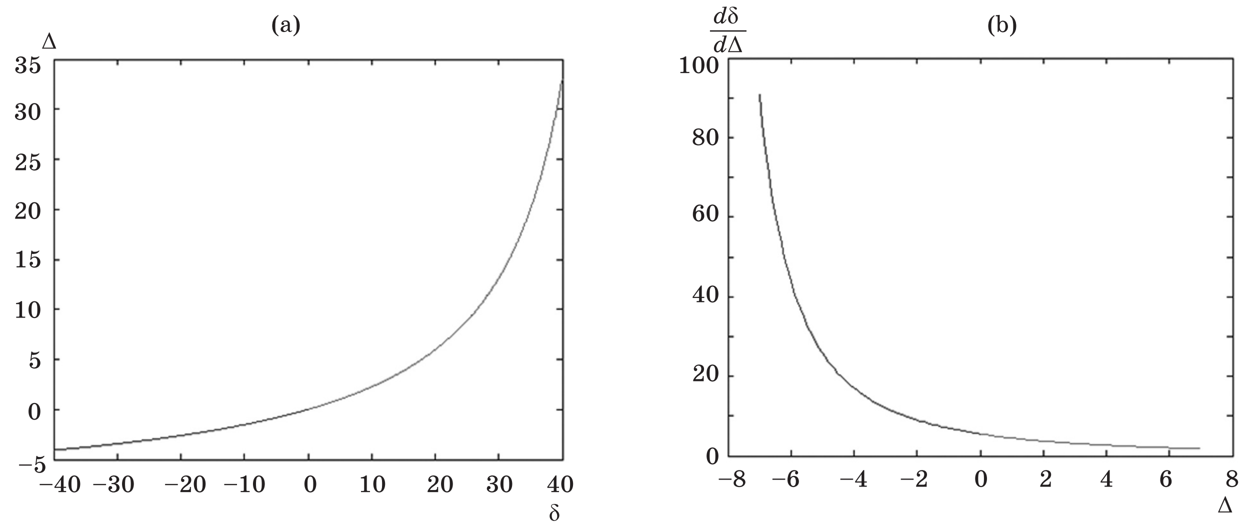


Fig. 5. The relations between: actual displacement and light spot displacement (a), and actual displacement and the displacement magnification (b).

If the measured surface moves down from the reference position, it's "+" in this formula, otherwise, it's "–". As shown in fig. 5.

From fig. 5, the relation between Δ and δ is non-linear. According to lens imaging law, in order to acquire clear and stable image to reduce errors, the common imaging magnification of system is 1.2 to 2.5. To reach micron grade in measuring range, the imaging amplification in this paper was set as 2.5.

The focal distance of the imaging lens used in the experiment of this paper is 20 mm, then we can get the object distance is 28 mm and the image distance is 70 mm. Large scattering angle will lead to astigmatism and distortion problems, so in this experiment the scattering angle was set as 30°.

As the non-linear relation between actual interface displacement and light spot displacement, it makes a very strict requirement for CCD length in optical imaging system. From formula (2) one can get CCD length formula

$$l_{\mathrm{ALL}} = \frac{\Delta l' \sin\theta}{l\sin\varphi - \Delta\sin(\varphi+\theta)} + \frac{\Delta l' \sin\theta}{l\sin\varphi + \Delta\sin(\varphi+\theta)} . \quad (7)$$

The length of the CCD used in the experiment of this paper is 55 mm and its image element spacing is 4 μm. From the formulas above, the precision of the surface displacement measurement can reach micron level when the displacement is below 3.5 mm.

4. Experimental results and analysis

4.1. Results comparison of center of gravity method and correlation method

With the diagrams in fig. 4 and the parameters set above, we can get the signals both with weak

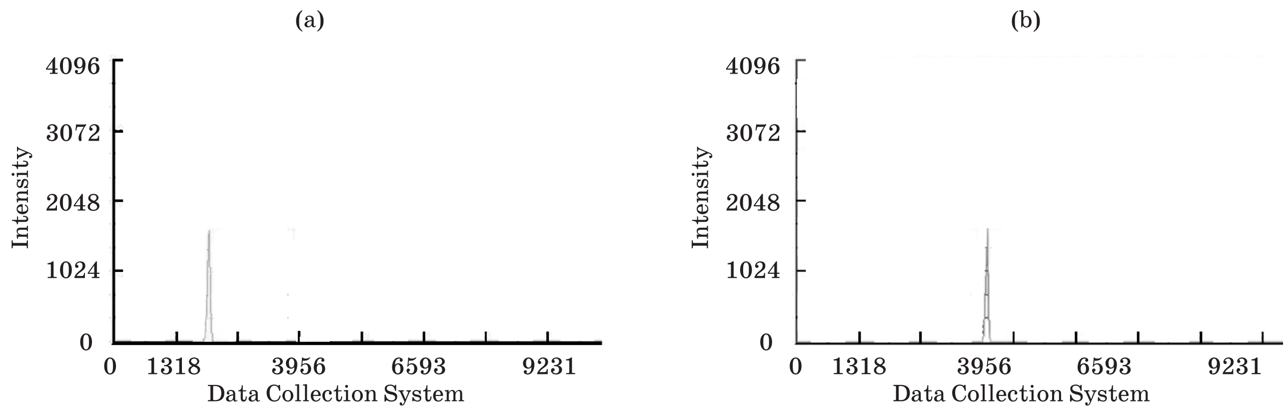


Fig. 6. Signals with weak scattering before displacement (a), after displacement (b).

Results comparison of center of gravity method and correlation method

Testing number	1	2	3	4	5	6	7	8	9	10
Actual displacement, mm	0.337	0.740	1.145	1.361	1.667	1.94	2.183	2.548	2.739	3.239
Center of gravity	0.346	0.721	1.104	1.324	1.630	1.890	2.133	2.477	2.665	3.135
Errors	2.8	2.6	3.6	2.7	2.2	3.3	2.3	2.8	2.7	3.2
Correlation method, mm	0.341	0.755	1.130	1.384	1.645	1.909	2.159	2.499	2.703	3.194
Errors, %	1.2	2	1.3	1.7	1.3	1.8	1.1	1.9	1.3	1.4

and strong scattering from the data collection system, as shown in fig. 6 and 7.

Coated a smooth surface with fine aluminum powder to make a simulation of rough interface, at this point it is the strong scattering surface. Moved the surface for 10 times and collected the signals, by the formula (2–5), respectively used center of gravity method and the correlation method in data processing. Results are shown in the table.

The results show that the digital correlation method is feasible in triangulation displacement measurement system, the precision can reach micron level and the experimental errors are below 2%. They are better than the results of center of gravity method in the situation of strong scattering.

4.2. Results comparison of interfaces with different roughnesses

Used the same smooth specimens in the following tests, and respectively coated them with 80 mesh aluminum powders, fine silica particles and 40 mesh aluminum powders. And then one can use surface profiler to get their surface contour curves, as shown in fig. 8. Their roughness parameters R_α are 6.54, 16.6 and 27.6 μm, they are respectively equivalent to the surface conditions of milling, planer and coarse grinding.

Measured the displacement by correlation algorithm again with the 3 conditions above and got the results as shown in fig. 9.

In fig. 9, X axis is the true values of displacement; Y axis is the values of correlation algorithm. The results show that measurement values and the actual values are in good agreement with the increase of the roughness of interface. It indicates that the correlation algorithm is applicable to all kinds of rough surfaces in triangulation displacement measurement.

4.3. The influence of oblique angle and color of interface

In the experimental system, errors of optical components which formed the measuring system are from spherical aberration, astigmatism, curvature of field and distortion etc; they will make the actual image point deviate from the ideal image point. The reducing of these errors depends mainly on the manufacturing processing. In a

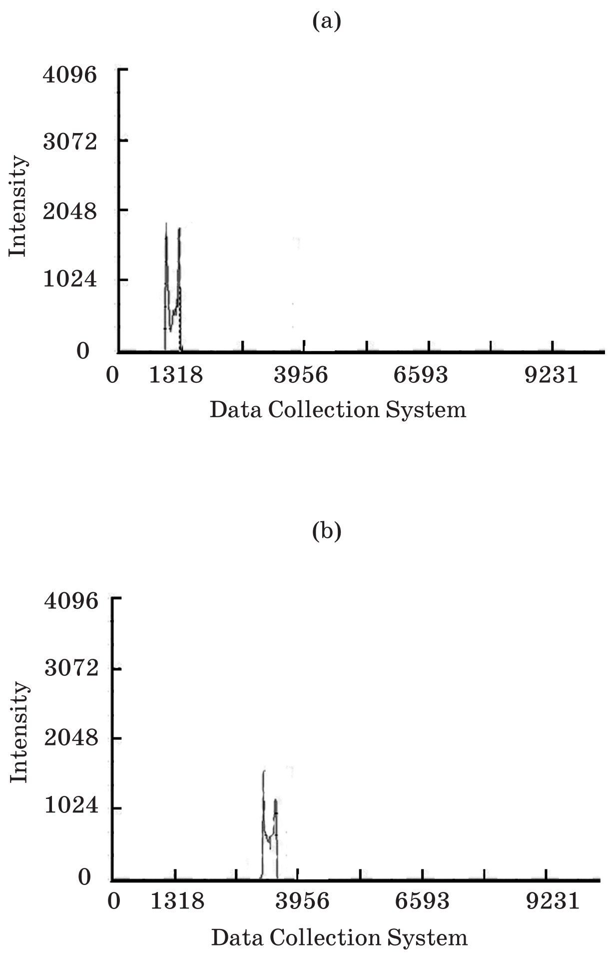


Fig. 7. Signals with strong scattering before displacement (a), after displacement (b).

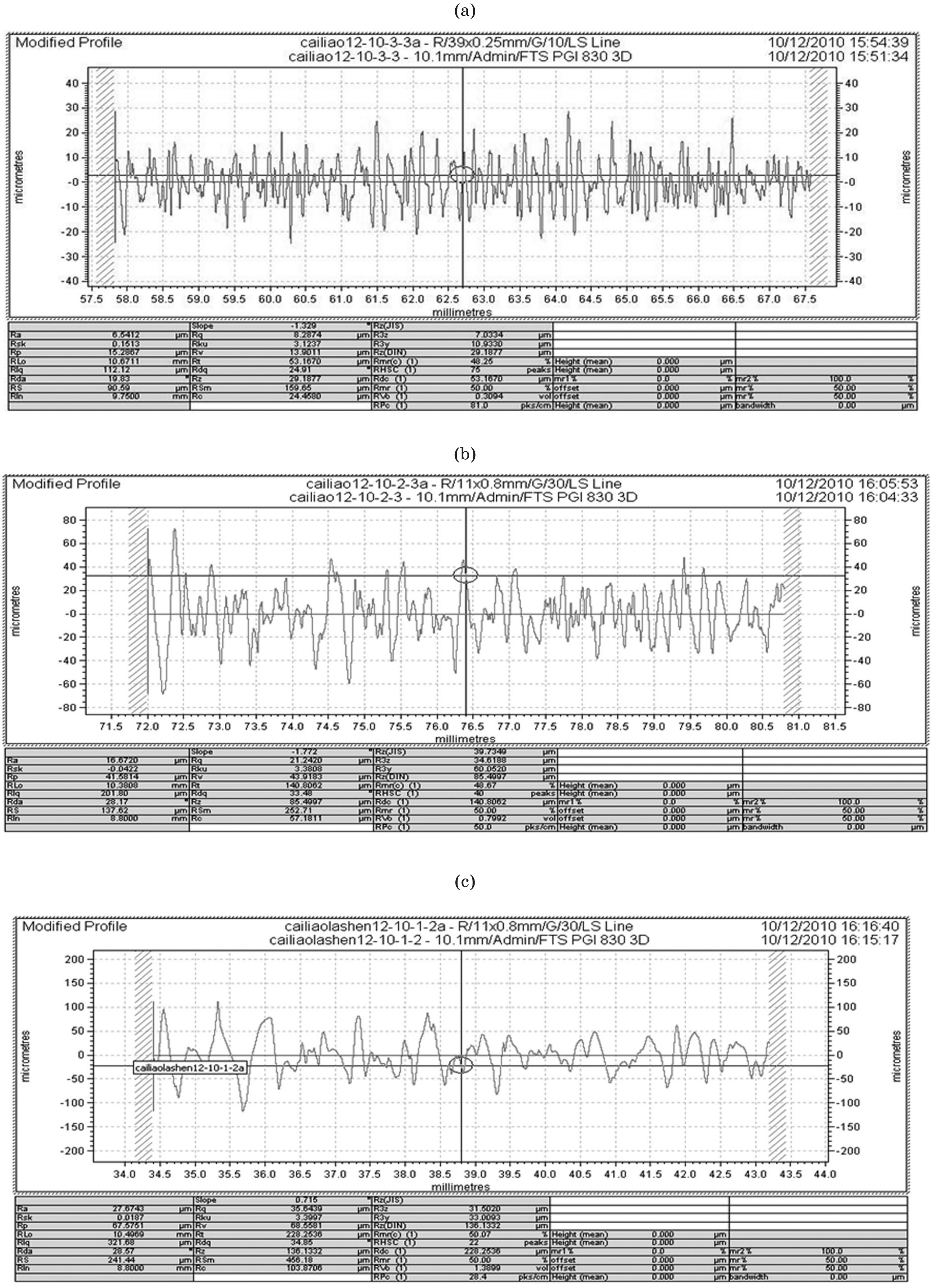


Fig. 8. Interface contour curve coated with different materials 80 mesh aluminum powder (a), fine silica particles (b), 40 mesh aluminum powder (c).

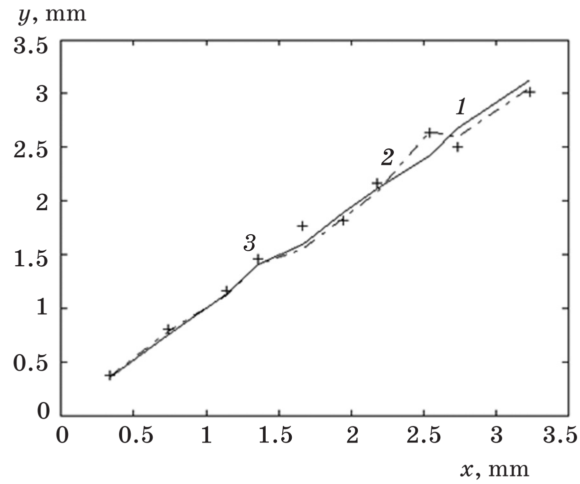


Fig. 9. Results comparison of interfaces with different roughnesses. *1* – 80 mesh aluminum powder, *2* – silica fine particles, *3* – 40 mesh aluminum powder.

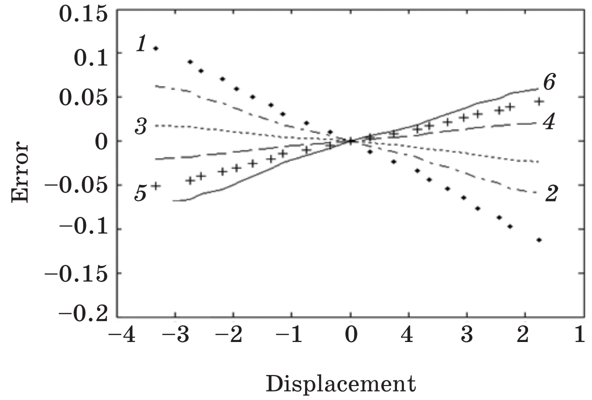


Fig. 10. Errors in strong scattering with different oblique angles. *1* – −30°, *2* – −20°, *3* – −10°, *4* – 10°, *5* – 20°, *6* – 30°.

certain circumstance of optical device, measuring accuracy is mainly affected by the following two aspects.

1. The oblique angle

When the normal direction of the interface is not consistent with the incident light, the angle between them is called oblique angle. With the difference of the oblique angles, the space distributions of the speckles produced by scattering are not the same, so that the optical signals received by CCD will change correspondingly. This leads to the deviation of center of gravity of light spot in weak scattering condition and also the decrease of correlation effect in strong scattering condition. So the actual results and theoretical results of triangulation measurement principle formula have a certain amount of deviation. Based on the strong scattering interface experiments, this paper tested interfaces with 6 oblique angles (10°, 20°, 30°, −10°, −20°, −30°) using the correlation method, and obtained the errors as shown in fig. 10.

This figure show that the errors rise with the increase of the oblique angle in the condition of the same displacements, and also rise with the increase of the displacement in the condition of the same oblique angles.

2. The color of interface

As the interfaces with different colors have different absorption rates to laser, the measurement accuracy will be influenced by colors. Therefore, in this paper, experiments on materials with different colors (red, orange, yellow, green, purple five colors) were made respectively. Experiments show that, from red to purple, the signal intensity on CCD is gradually weakened. The self-adaptive control of light intensity can be used to solve the influence of color on the measurement results.

Conclusion

This paper established the laser triangulation measurement system, used the digital speckle correlation method to measure the displacement of rough interface with strong scattering, and the results had been compared with those of traditional center-of-gravity method. The results show that the digital correlation method is feasible in triangulation displacement measurement system, the measuring range can reach micron grade and the experimental errors are below 2%, this method is better than the center-of-gravity method in strong scattering condition. This paper also measured interfaces with different material properties, analyzed the influences of different surface roughnesses, surface colors and oblique angles on the results of measurement. The method proposed in this paper can overcome the disadvantage of triangulation system in the situation of rough interface with strong scattering and improve the measurement accuracy.

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REFERENCE

1. *Zhou Zhenshu*. Non contact measurement of laser optical probe // J. Optics and precision engineering in China. 1997. V. 5. № 3.
2. *Nakadate S., Yatagai T., Saito H*. Computer-aided speckle pattern interferometry // Appl. Opt. 1983. V. 2. № 2. P. 237–243.
3. *Diaz F.V., Kaufmamm G.H*. Impact-induced transient deformation analysis by means of digital speckle interferometry // Exp. Mech. 1999. V. 39. № 4. P. 311–316.
4. *Crutis D.M., Hao Zhang, Kenneth J.V*. Effects of optically shallow bottoms on upwelling radiances: Bidirectional reflectance distribution function effects // Limnol. Oceanogr. 2003. V. 48. № 1. P. 2, P. 337–345.
5. *Maradudin A*. Backscattering effects in the elastic scatter of polarized light from a large-amplitude random metallic grating. Scattering in Volumes and Surface. North-Itolland: Elsevier Science Publishers BV, 2000. P. 157–174.
6. *Francis D., James S.W., Tatam R.P*. Surface strain measurement of rotating objects using puslsed laser shearography with coherent fibre-optic imaging bundles // Measurement Science and Technology. 2008. V. 19. № 10. P. 1–13.
7. *Jin Guanchang, Meng Libo*. Digital speckle correlation technique development and application // J. Experimental mechanics in China. 2006. V. 21. № 6. P. 689–702.