A new subdivision technique for grating based on CMOS microscopic imaging

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We propose a new subdivision technique directly subdividing the grating stripe by using complementary metal-oxide semiconductor (CMOS) microscopic imaging system combined with image processing. The corresponding optical system, subdivision principle, and image processing methods are illuminated. The relations of systemic resolution to subdivision number, grating period, magnifying power and tilt angle are theoretically discussed and experimentally checked on the Abbe comparator. The measurement precision for displacement of the proposed subdivision system is tested in the range of 5 mm and the maximum displacement error is less than 0.4 μm. The factors contributing to the systemic error are also discussed.

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Metrological grating technique has been widely used for displacement measurement in many industrial fields at present[1,2]. Usually, various means are employed to enhance the resolution, including optical subdivision, mechanical subdivision, electric circuitry subdivision, and so on[1,3,4]. These subdivision means almost focus on obtaining multiple signals in one period of moiré fringe, which is generated from a pair of gratings with a small tilt angle. However, the optoelectronic signal of moiré fringe tends to be influenced by numerous factors such as error introduced by grating production, tilt angle of two gratings, illumination device, etc., and reducing the errors from these factors results in the complexity and high cost of measurement system[5−7]. So it limits the further improvement on the resolution of moiré displacement device. In order to solve this problem, some investigations on avoiding the errors from moiré fringe have been done by using complementary metal-oxide semiconductor (CMOS) image sensor in our previous studies[8,9]. In the present work, a new technique to directly subdivide the grating fringe is proposed and tested experimentally, using CMOS microscopic imaging system combined with image processing. The signals of grating fringe are obtained instead of those of moiré fringe by CMOS image sensor, and one grating pitch is subdivided directly by CMOS pixels. Thereby the errors arising from moiré fringe are avoided. Compared with other techniques based on moiré fringe, the present method has the advantages of higher quality signal, lower request for illumination device and smaller influence from grating production error, which contribute to higher measurement precision.

The optical system is shown in Fig. 1. A normal white light source is employed in the system, whose intensity can be adjusted to avoid the saturation in the CMOS image sensor. One grating is placed between the light source and a microscopic objective, and is fixed on the displacement platform to guarantee that the grating fringe is vertical to the motion direction. The grating illuminated by the light source is magnified by the microscopic objective and the corresponding image is received by CMOS image sensor. In the end, the image is sent into personal computer for analysis. It is noted that the system has an optimum resolution as the magnifying power matches with CMOS array.

The subdivision principle is shown in Fig. 2. The grating is imaged in CMOS array as there is a tilt angle θ between the grating fringe and the pixel column of CMOS array. One point in the CMOS array is firstly selected as reference point, which is marked as O in Fig. 2. Then two edge points of one grating stripe marked A and B in Fig. 2 can be detected in the same column as point O and they are nearest to point O in the upward and downward directions, respectively. Obviously, the grating pitch is subdivided by the pixels in the line AB. The relative position of the reference point O in line AB can be calculated by L_{AO}/L_{OB}, where L_{AO} and L_{OB} are the lengths from points A and B to point O, respectively. The

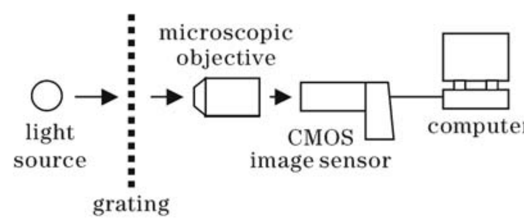

Fig. 1. Schematic of the optical system.

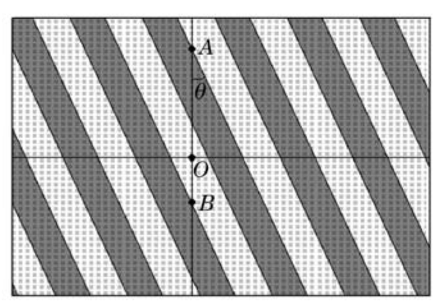

Fig. 2. Subdivision principle.

displacement can be calculated by comparing the relative positions of point O in line AB before and after motion. In practice, multiple reference points are employed in the displacement calculation to reduce the influence arising from the grating production error.

According to the subdivision principle, the systemic resolution δ can be simply written as

$$\delta = d/N, \quad (1)$$

where d is the grating period and N is the subdivision number or the pixels number in line AB. For example, the systemic resolution reaches 20 nm if the grating period is 20 μm and the subdivision number is 1000. It can be concluded from Eq. (1) that if the grating period is fixed, the more the subdivision number is, the higher the systemic resolution is. If the imaging system is taken into consideration, this conclusion should be adjusted.

Supposing that magnifying power of subdivision system is a and the size of the pixel in CMOS array is $b \times b$, the object-image scale relation is obtained as

$$\frac{d}{\sin\theta} \cdot a = b \cdot N. \quad (2)$$

Combined Eqs. (1) and (2), the systemic resolution δ can also be expressed as

$$\delta = \frac{b}{a}\sin\theta. \quad (3)$$

If pixel size and tilt angle are fixed, it can be concluded from Eq. (3) that the higher the systemic resolution is needed, the larger the magnifying power should be. But once the magnifying power is too large, the quality of the grating image received by CMOS array becomes low and unsuitable for image processing. So the magnifying power limits the systemic resolution in some degree. It is advisable that the magnifying power of microscopic objective is no larger than 40× in practice. In addition, the systemic resolution is higher as the tilt angle is smaller, as can be seen from Eq. (3). But if the tilt angle is too small, two edge points of one grating stripes cannot be detected in the same column of CMOS array, which can be seen from Fig. 2. Then the proposed subdivision technique cannot be implemented. Considering the triangular geometry, the tilt angle must be larger than the critical angle θ_c, which can be estimated as

$$\theta_c = \sin^{-1}(2 \cdot d/L), \quad (4)$$

where L is the length of CMOS array.

Image processing is very important in the proposed subdivision technique because it has the functions of removing the redundant information in the grating image and simplifying the displacement calculation. According to the subdivision principle, only the boundaries of grating stripes are useful for the subdivision. So after obtaining the grating image, it is necessary to find out the edges of grating stripes with the methods of image processing before displacement calculation. Here, binarization and edge-detecting are sequentially employed. Firstly, the original image is converted to the binarized image by setting a gray-scale threshold. It must be careful to determine the gray-scale threshold for the original image because the threshold has influences on the boundaries of grating stripes in the binarized image, which will contribute to the measurement precision. The iteration method to obtain the best threshold[10] was employed in our algorithm for binarization. Secondly, the edges in the binarized image are detected by using Canny operator[10]. In fact, Canny operator is a little complicated for us since the grating image is very simple and regular. The effects of image processing are shown in Fig. 3. It is seen that the quality of the grating image received by CMOS array is high and the edges of grating stripes can be detected precisely, which indicates that the image processing can work well.

The measurement system as shown in Fig. 4 was set up according to the subdivision principle and its performance was tested on the Abbe comparator with a minimum scale mark of 1 μm. The measurement precision was firstly investigated for the subdivision systems with different systemic resolutions. It can be concluded from the above theoretical analysis that subdivision number, grating period, magnifying power and tilt angle are all the factors contributing to the systemic resolution. So different hardware, such as two types of gratings and two types of CMOS image sensors both distinguished by 'I' and 'II', were employed to set up the subdivision system. The periods of gratings I and II are 100 and 20 μm, respectively. And the total pixel numbers of CMOS sensors I and II are 640 × 480 and 1280 × 1024, respectively. In the experiment, the magnifying power was adjusted by switching microscopic objectives and tilt angle was changed by rotating CMOS image sensor. It is noted

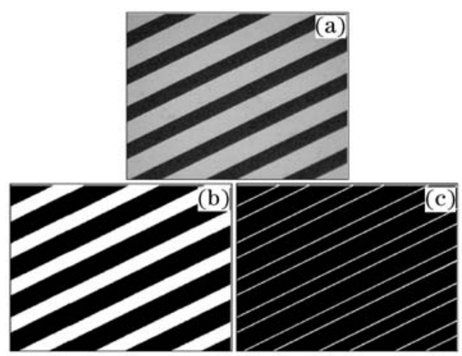

Fig. 3. Effects of image processing. (a) Original image; (b) binarized image; (c) edge-detected image.

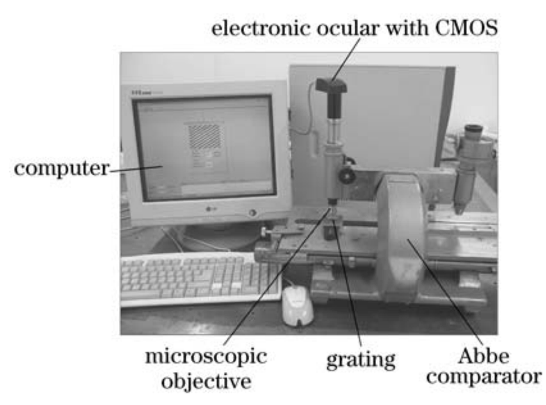

Fig. 4. Experimental setup.

Table 1. Performances of the Measurement Systems with Different Resolutions

Measurement System	1	2	3	4	5
Grating	I	I	I	I	II
CMOS	I	I	II	II	II
Tilt Angle (deg.)	90.00	20.25	18.00	56.25	19.13
Amplifying Power	4.7	4.8	6.3	26.0	26.0
Resolution (μm)	1.0	0.4	0.2	0.1	0.04
Maximum Error (μm)	0.8	0.66	−0.52	−0.39	0.20

Note: The periods of gratings I and II are 100 and 20 μm. The pixel numbers of CMOS sensors I and II are 640 × 480 and 1280 × 1024, and their pixel sizes are 5.04 × 5.04 and 3.18 × 3.18 (μm), respectively.

that the magnifying power of subdivision system is not equal to that of microscopic objective and is calculated according to Eq. (2) in practice. Tilt angle was measured through straight line fitting for grating lines by software automatically. The subdivision systems 1 to 5 were set up in the experiment, which have the resolutions of 1.0, 0.4, 0.2, 0.1, and 0.04 μm, respectively. The measurement precisions of these subdivision systems were tested in the distance range of one grating period by stepping one-tenth of one grating pitch. The corresponding maximum displacement errors of each subdivision system are shown in Table 1, which indicate that the higher the resolution is, the better the system performs. At present, the subdivision system 5 consisting of grating II, CMOS II and 40× microscopic objective has the optimum resolution of 0.04 μm and its maximum displacement error is 0.20 μm. The performance of subdivision system 5 was then tested in a longer distance range of 5 mm by stepping 100 μm and the results are shown in Fig. 5. It can be observed from Fig. 5(a) that the linearity of subdivision system 5 is 0.9998. Repeated experiments have been done for the subdivision systems with different resolutions and it has been found that the linearity of this subdivision technique is better than 0.99. The maximum displacement error of subdivision system 5 is less than 0.4 μm, which can be clearly seen from Fig. 5(b).

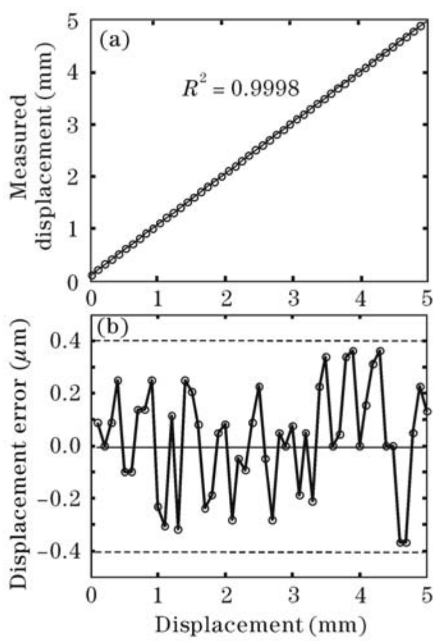

Fig. 5. Displacement errors of the proposed subdivision system in the measurement range of 5 mm.

The measurement precision of the subdivision system is affected by some factors, in particular the errors from displacement platform and the quality of grating image. Obviously, the displacement accuracy of measurement system cannot be higher than that of displacement platform. Especially, if the grating stripe is not strictly vertical to the displacement direction, the displacement error increases as the displacement increases. The quality of grating image plays a key role in the image processing. If the grating lines are ambiguous or the resolution of grating image is not high enough, the edges of grating stripes cannot be detected precisely and then the displacement cannot be measured accurately. The simple way to obtain the grating image with high resolution is to employ the CMOS image sensor with high resolution. Additionally, the edges of grating stripes are the only useful information for the proposed subdivision technique, and the accuracy of edge-detecting in software will also affect the measuring precision. So it is very important to improve the algorithm of edge-detecting to eliminate the measurement errors, which will be investigated in further research.

In conclusion, a novel subdivision technique directly subdividing the grating stripe was studied theoretically and experimentally to enhance the resolution, which can avoid the errors arising from moiré fringe in the traditional methods. It is easy to obtain the grating image with high quality and flexible to achieve the displacement calculation. Moreover, the measurement setup is very simple and not inclined to be infected by the circumstance. At present, the resolution of the measurement system based on the proposed subdivision technique could reach 0.04 μm and its maximum displacement error in the measuring range of 5 mm could be less than 0.4 μm.

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