A new interpolating method based on the variation of spectra energy using CMOS array

Tianjin Tang (汤天瑾), Xiangqun Cao (曹向群), Hongqiu Chen (陈洪璆), and Bin Lin (林 斌)

CNERC for Optical Instrument, Zhejiang University, Hangzhou 310027

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A new interpolating method to enhance the resolution of gratings using complementary metal-oxide semiconductor (CMOS) according to the variation of some specified spectral light intensities during the motion of scale grating in a periodic separation is proposed. CMOS image sensor (pixel array 648 × 488) was also introduced as receiving device and its stability was verified experimentally. Many factors in the experiment were analyzed theoretically and contrasted with experiment. The advantages of this novel method were featured by CMOS and the specified spectral variation of the energy distribution was discussed.

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There are various means to enhance the resolution of gratings for the moment, such as optical interpolation, mechanical interpolation, and interpolation by software and electronic circuitry, and so on. All of these interpolating methods aim at obtaining multiple electronic signals in a period of moiré fringe. However, the quality of photoelectric signal of the moiré fringe is affected by many factors, such as the error introduced by the production of gratings, the illuminating device (the width of the light resource and whether the light beam is parallel), and the receiving device, etc.. It is usually difficult to obtain moiré fringe with high quality, which limits the interpolating precision. In order to solve this problem, a new interpolating method based on the spectra of gratings was studied experimentally, complementary metal-oxide semiconductor (CMOS) image sensor was introduced to receive the spectra due to its remarkable advantages such as better image quality, lower power consumption, higher integration, and higher resolution, contributed to high systemic precision. The spectra of two superposed gratings were received and observed by CMOS, the resolution of gratings was enhanced by means of interpolation according to the various light intensities during the movement of the scale grating in a period's separation. Based on diffractive theory, every grating has its own observable spectrum with steady energy. This new method does not deal with the photoelectric signal of the moiré fringe directly but the steady spectra. Thereby the unfavorable influences of the bad photoelectric signal was avoided. As is known, an amplitude grating can be regarded as the composed result of many sinusoidal gratings. To avoid the disadvantageous influence induced by the harmonics with high frequencies, only the spectra with orders 0 and ±1 were accepted.

The optical system is shown in Fig. 1. A 4-mW laser diode was employed in this system. The collimated red light was cast vertically onto two superposed rectangle gratings. The two gratings have same period (10 μm). They were placed with zero degree between their slits. The minimum scale mark of a slit disk was 1 μm, the lead screw was fixed on the center of the disk. The lead screw moved by rotation of the slit disk, and the scale grating moved along with the lead screw, the displacement of the lead screw was one calibration period when the slit disk rotated for one circle. Supposing n is the total number of the slits on disk and L' is the calibration period on lead screw, then L'/n is the resolution power that the system can reach theorically. Based on the slit disk and gratings, the scale grating moved for one period when the slit disk rotated for ten scales. After the silt disk rotated for 1 μm, we captured the spectra for one hundred times and calculated the average spectral light intensity. According to the variation of the certain order spectrum energy, ten interpolations can be realized. The space between two gratings is less than 1 mm. There was a diaphragm with an adjustable slit ranging from 0 to 0.4 mm, which can control the energy from light resource. A CMOS image sensor was placed behind the gratings to receive the spectra, the obtained image was sent to PC via USB transmission lines and was displayed at the same time. Different orders of spectra can be captured synchronously or individually by changing the space between the gratings and CMOS.

Illumination uniformity was the most important, unbalanced illumination was disadvantageous to the following interpolation. The CMOS was placed far away from the rosters to receive the distribution of the light intensity. According to the spectral energy distribution, we can bear out whether the balancing illumination was satisfied or not. From Fig. 2, we can conclude that it conforms approximately to Gaussian distribution, even the illumination can be assumed in our experiment

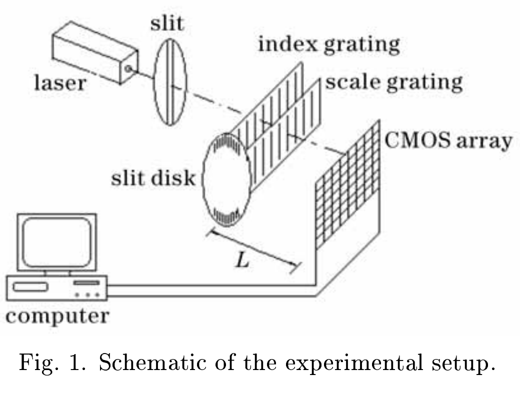

Fig. 1. Schematic of the experimental setup.

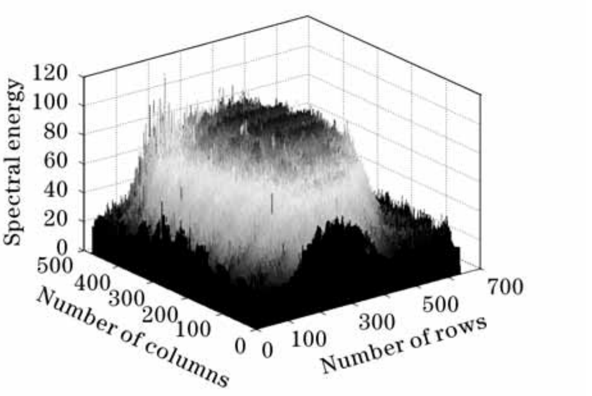

Fig. 2. Distribution of light intensity.

because the width of the slit was far less than the diameter of the light source.

Supposing d is the period of the gratings, a and b are the width and length of the CMOS, w is the width of the slit on the diaphragm placed behind the light source. Based on the two basic equations of gratings, given that β is the diffractive angle when light passes through the second grating, then the light intensity distribution behind the second grating can be described by

$$d \sin\beta = (m+n)\lambda, \tag{1}$$

where $(m+n)$ can be seen as integrative order, and the emitting light with the same integrative order contributes to spectrum with same order. The half width of the stripe $\Delta\beta$ should be considered to receive the whole stripe, then we have

$$\begin{aligned} l &= \frac{b}{2} \cdot \frac{1}{\tan(\beta + \Delta\beta)} \\ &= \frac{b}{2} \cdot \frac{1 - \frac{(m+n)\lambda}{\sqrt{d^2-(m+n)^2\lambda^2}} \tan\left(\frac{\lambda}{N\sqrt{d^2-(m+n)^2\lambda^2}}\right)}{\frac{(m+n)\lambda}{\sqrt{d^2-(m+n)^2\lambda^2}} + \tan\left(\frac{\lambda}{N\sqrt{d^2-(m+n)^2\lambda^2}}\right)}. \end{aligned} \tag{2}$$

To avoid the aliasing of stripes, the distance between CMOS and the second grating is less than l.

During the movement of the scale grating, one of the two gratings has alterable area as illuminated from 0 to half the pitch because the distance between two gratings is small. Assuming P is a spot to be observed on the spectrum face, α is diffractive factor of single slit, N is the number of the slits where light can penetrate, and δ is the phase difference produced by single slit on P. The light intensity on P can be expressed as

$$I(P) = I_0 \left(\frac{\sin\alpha}{\alpha}\right) \left[\frac{\sin(N\delta/2)}{\sin(\delta/2)}\right]. \tag{3}$$

The light intensity on P is determined by the diffractive factor of single slit and the interferential factor of slits of the grating. Based on the expressions of α, δ and Eqs. (1) and (2), Eq. (3) can be written as

$$I(P) = I_0 \left[\frac{\sin(kla/2)}{kla/2}\right] \left\{\frac{\sin[(m+n)w\lambda/2]}{\sin[(m+n)\lambda/2d]}\right\}, \tag{4}$$

where k and l are constants because the distribution of the spectra in the space behind the gratings is certain as soon as the gratings are settled. It is obvious that the light intensity on P relates to three factors I_0, w, and a (the width of the transmitted area in a period's separation on the grating). The light intensity of spectrum with the order 0 which is the maximum can be given by

$$\begin{aligned} I(P) &= I_0 \left[\frac{\sin(kla/2)}{kla/2}\right] \\ &\quad \times \lim_{\delta \to 2k\pi} \frac{2\sin(N\delta/2)\cos(N\delta/2)\cdot(N/2)}{2\sin(\delta/2)\cos(\delta/2)\cdot(1/2)} \\ &= I_0 \left[\frac{\sin(kla/2)}{kla/2}\right] N^2. \end{aligned} \tag{5}$$

$I(P)$ is maximum when w is $d/2$. The appropriate luminous intensity to the CMOS can be realized by adjusting the light intensity behind the diaphragm. There are two means, using the light source under lowered voltage and reducing the aperture of the diaphragm, which are often combined in actual operation. High red sensitivity, dynamic range, and fill factor are also to be considered. HV7131E1 CMOS is used, and several electro-optical characteristic parameters are: total pixel array 648 × 488, pixels size 8×8 μm^2, fill factor 30%, red sensitivity 2100 mV/(lux·s), and maximum dynamic range 48 dB.

Different types of CMOSs respond to different ranges of illumination intensities. Saturation develops when the light intensity received by CMOS is more than the maximum and no pattern can be observed when less than the minimum, each of them would result in unfaithful conclusion or even total failure of the experiment. Therefore, the luminous intensity of the CMOS must be limited to a certain range to ensure the clearest observation. That is to say the inequation $E_{\text{m}} < E < E_{\text{M}}$ must be satisfied here, in which E_{m} and E_{M} denote the minimum and maximum luminous intensities of the CMOS. E_{M} and E_{m}, relating to the frame rate, sensitivity, and so on, were calculated to be about 0.1 and 4.36 lux respectively based on the above parameters. In the experiments, when operating voltage was fixed at 1.95 V and the spectra with orders 0 and ± 1 were observed, CMOS could receive moderate luminous intensity only under the condition that the width of the adjustable slit ranged from 45 μm to 0.38 mm. The instability of the CMOS by repeated experiments for one hundred times was less than 4.75%, as shown in Fig. 3.

The traditional device to capture spectrum was power meter, under the same condition, the stability of power meter is shown in Fig. 4 (drift percentage of the spectrum with the order -1).

The maximum drift percentage was over 25%. Compared with the traditional receiving device such as charge-coupled device (CCD), the performance of CMOS improved distinctly. A/D translator, sequence and controlling circuits, and signal processing were all integrated on-chip. Lower power resumption, higher sensitivity, and improved signal-to-noise ratio contributed to the systemic precision.

There are small areas between adjacent pixels on

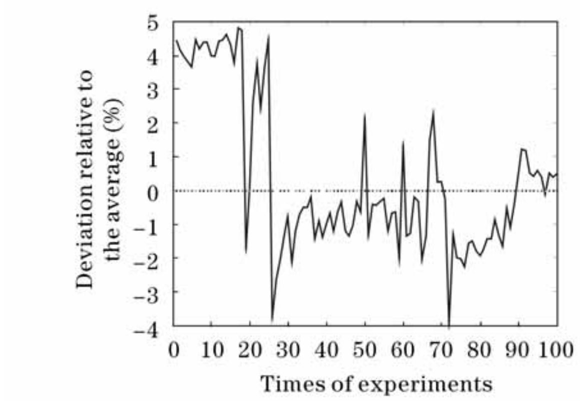

Fig. 3. Drift percentage of the spectra captured by CMOS.

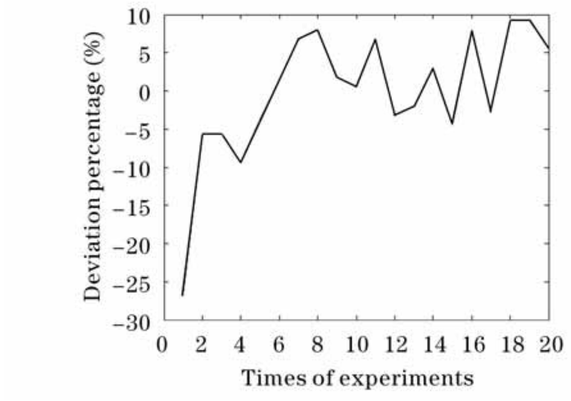

Fig. 4. The stability of power meter.

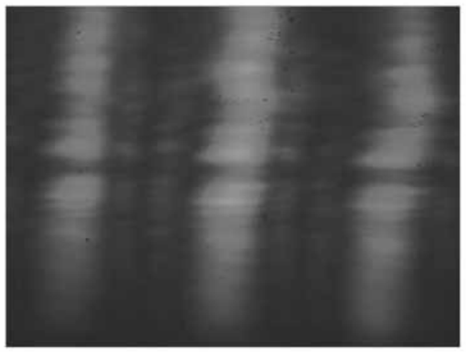

Fig. 5. The spectra with three orders 0 and ±1.

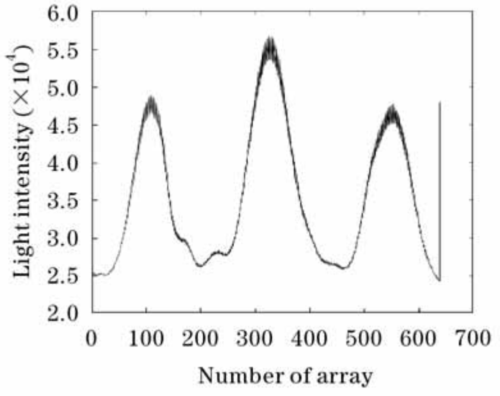

Fig. 6. Spectral energy distribution curve.

CMOS, which often bring about unavoidable testing error especially when the light intensity varies little in two spectra images. Accordingly, the best match between the shape of the illuminating source and the CMOS must be accomplished to fully utilize the pixels and reduce error. The luminating source with a shape of roundness or rectangle can be used in this system. It is obvious that more pixels can be utilized when the shape of the light source is rectangular because the shapes of the spectrum and the light source are uniform. In this system the shape of spectrum is achieved by placing a diaphragm with a slit on it behind the light source closely. It was also feasible to place a cylindrical lens before the gratings. The image of the round light-house was spread to gain approximately rectangular spectra on CMOS.

The spectra with orders 0 and ±1 are shown in Fig. 5, the operating voltage was set to be 2.0 V and the width of the diaphragm was 0.375 mm, the corresponding spectral energy distribution curve was illustrated in Fig. 6.

Obviously there was high-order harmonic frequency causing the fluctuant distribution especially at wave crest, as shown in Fig. 6. From it, we could find that the more narrow the width of the adjustable slit, the more undulate the energy distribution current at the wave crest and trough, and the stripes between two orders of spectra are more clear. So we can conclude that the spectra of gratings mixed by the shadows of gratings and the diffractive image of the slit have been captured all together by CMOS. Filtering analysis was absolutely necessary. How to separate them and obtain simplex image of the spectrum was also necessary to be studied afterwards.

In conclusion, a novel interpolating method dealing with spectrum directly was studied experimentally to enhance the resolution of gratings, which avoids the disadvandages that moiré fringe with high quality is difficult to be achieved in many traditional methods. And it is easy to obtain stable images of spectra based on the favorable performance of CMOS. The setup was simple, and no inclination was infected by the circumstance. Real time measurement could be realized.

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