Non-piece-wise error compensation for grating displacement measurement system with absolute zero mark

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A method for compensating the measuring error of the grating displacement measurement system with absolute zero mark is presented. It divides the full scale range into piece-wise subsections and compares the maximum variation of the measuring errors of two adjacent subsections with the threshold. Whether the specified subsection is divided into smaller subsections is determined by the comparison result. After different compensation parameters and weighted average values of the random errors are obtained, the error compensation algorithm is implemented in the left and right subsections, and the whole measuring error of the grating displacement measurement system is reduced by about 73%. Experimental results show that the method may not only effectively compensate the spike error but also greatly improve the precision of the measuring system.

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Recently, with the fast development of the instrument manufacturing industry, the need of high measuring precision of the grating displacement measurement system becomes urgent. However, the characteristics of materials and the manufacturing techniques limit the improvement of the measuring precision[1−3]. So it is necessary to find an effective method to improve the measuring precision of such systems. There are two methods of error correction utilized in the grating displacement measurement system with absolute zero mark[4−6]. One is the full scale method that uses one correction parameter to linearly compensate the error in the full scale range. The method is convenient but the precision of the error-compensated measurement system is low when the error changes in a nonlinear way. The other is piece-wise subsection method that divides the full scale range into piece-wise subsections and each subsection corresponds to a compensation parameter[7,8]. When the variation of the measuring errors of two adjacent subsections changes small, the method can improve the precision of the measuring system. While when the variation changes great, in practice, it is found that the method could not effectively compensate the error of the measuring system. The bigger variation of the measuring errors of two adjacent subsections is referred to as the spike error.

In this letter, the error characteristics of the grating displacement measurement system with absolute zero mark are analyzed. A method is proposed which divides the subsection with spike error into smaller subsections and separately compensates the measuring error in the left and right subsections. This method may overcome the shortages of the traditional methods and improve the measuring precision of the grating displacement measurement system.

The measuring system is composed of a grating sensor module, a shaping and subdivision module, an identification module, a counting and buffering module, and a microprocessor and display module. The grating sensor module is composed of the main grating, the index grating, the lens, and the light emitting diode (LED) source whose wavelength is 880 nm. After the light is collimated by the lens, the relative movement between the main grating and the index grating will result in the moiré fringe. The image of the fringe is received by the optoelectronic receivers and transformed into the sine signal. A period of the sine signal corresponds to the grid width of the grating sensor module. By means of shaping, dividing, and counting the signal, the information of displacement that is relative to the absolute zero mark may be obtained by the measuring system[9,10]. When the grating sensor module with the grid of 20 μm is utilized, the resolution of 1 μm is obtained by dividing the signal 20 times. After the subdivided signal from the shaping and subdivision module enters the identification module, the signal is identified. The counting and buffering module processes the identified signal, implements the addition or subtraction algorithm, and temporarily stores the counting values. The microprocessor and display module acquires and processes the counting values, and then displays the value of displacement.

The value of displacement includes the error of the measuring system, which has three characteristics[11]. The first one is the continuity. When the distribution of the galvanization layer of the etch lines is well-proportioned and the etch lines are arranged equidistantly, the sine signal continuously changes in the full scale range, which makes the error of the displacement continuously change in the full scale range. The second one is the coarseness. When the well-proportioned distribution of the galvanization layer of a series of etch lines is seriously destroyed, the amplitude, phase, and frequency of the sine signal show an obvious change that produces the spike error in the small section. The last one is the error distribution. Since the error of the measuring system appears in a distributed pattern along two sides of the mark, the mark may be considered as the original position to implement the error correction.

Before the error correction is implemented to the left and right sides of the mark, the left and right subsections are divided equidistantly and the measuring errors of the subsections are obtained. Let $\alpha_{\mathrm{l}i}$ be the variation of the measuring error of two left divided adjacent subsections, and $\alpha_{\mathrm{r}k}$ be the variation of the measuring error of two right divided adjacent subsections, we can get

$$\alpha_{\mathrm{l}i} = |\delta_{\mathrm{l}i} - \delta_{\mathrm{l}i-1}|, \quad (1)$$

$$\alpha_{\mathrm{r}k} = |\delta_{\mathrm{r}k} - \delta_{\mathrm{r}k-1}|, \quad (2)$$

where $\delta_{\mathrm{l}i}$ is the measuring error of the ith left subsection, and $\delta_{\mathrm{r}k}$ is that of the kth right subsection. When $\alpha_{\mathrm{l}i}$ or $\alpha_{\mathrm{r}k}$ exceeds the expected threshold, the spike error is considered. The subsection with bigger error will be divided again. Otherwise the divided subsection maintains unchanged. Let N_1 be the number of the left divided subsections, $X_{\mathrm{l}i}$ $(i = 1, 2, 3, \cdots, N_{\mathrm{l}})$ be the displacements relative to the mark, $S_{\mathrm{l}i}$ be the length of subsection i, and $\delta_{\mathrm{lc}}(i)$ be the parameter of subsection i to be compensated, we can get

$$\delta_{\mathrm{lc}}(i) = (\delta_{\mathrm{l}i} - \delta_{\mathrm{l}i-1}) \times \frac{x_{\mathrm{l}i} - \sum S_{\mathrm{l}i-1}}{S_{\mathrm{l}i}} + \delta_{\mathrm{l}i}. \quad (3)$$

In the similar way, let N_2 be the number of the right divided subsections, $X_{\mathrm{r}k}$ $(k = 1, 2, 3, \cdots, N_2)$ be the displacements relative to the mark, $S_{\mathrm{r}k}$ be the length of subsection k, and $\delta_{\mathrm{rc}}(k)$ be the parameter of subsection k to be compensated, we can get

$$\delta_{\mathrm{rc}}(k) = (\delta_{\mathrm{r}k} - \delta_{\mathrm{r}k-1}) \times \frac{x_{\mathrm{r}k} - \sum S_{\mathrm{r}k-1}}{S_{\mathrm{r}k}} + \delta_{\mathrm{r}k}. \quad (4)$$

When $\delta_{\mathrm{lc}}(i)$ and $\delta_{\mathrm{rc}}(k)$ are obtained by Eqs. (3) and (4), the compensation parameters can be utilized to compensate the systematic errors. If intermittent and momentary disturbance or noise exists in the measuring process, the measured values will include significant random errors[12]. Using the parameters for compensation, the error compensated curve will deviate from the expected one. Considering the influence of random errors, a statistical approach is explored to reduce it. Let $\varepsilon_{\mathrm{lc}}(i)$ be the deviation of the measured value of left subsection i from the average value computed over the measured data set, $\varepsilon_{\mathrm{rc}}(k)$ be that for the right subsection k, $P_{\mathrm{lc}}(i)$ be the probability of $\varepsilon_{\mathrm{lc}}(i)$, $P_{\mathrm{rc}}(k)$ be the probability of $\varepsilon_{\mathrm{rc}}(k)$, and $\overline{\varepsilon_{\mathrm{lc}}}(i)$ be the weighted average value of $\varepsilon_{\mathrm{lc}}(i)$, and $\overline{\varepsilon_{\mathrm{rc}}}(k)$ be the weighted average value of $\varepsilon_{\mathrm{rc}}(k)$, we can get

$$\overline{\varepsilon_{\mathrm{lc}}}(i) = \sum_{i}^{N_1} \varepsilon_{\mathrm{lc}}(i) \times P_{\mathrm{lc}}(i), \quad (5)$$

$$\overline{\varepsilon_{\mathrm{rc}}}(k) = \sum_{k}^{N_2} \varepsilon_{\mathrm{rc}}(k) \times P_{\mathrm{rc}}(k). \quad (6)$$

After $\overline{\varepsilon_{\mathrm{lc}}}(i)$ and $\overline{\varepsilon_{\mathrm{rc}}}(k)$ are obtained by Eqs.(5) and (6), the microprocessor implements the error compensation algorithm. The error compensation value of the left subsections is the sum of $\delta_{\mathrm{lc}}(i)$ and $\overline{\varepsilon_{\mathrm{lc}}}(i)$, and that for the right subsections is the sum of $\delta_{\mathrm{rc}}(k)$ and $\overline{\varepsilon_{\mathrm{rc}}}(k)$. The flow chart of non-piece-wise error compensation algorithm is shown in Fig. 1.

In our experiments, the grid width of the grating sensor was 20 μm, the interval between two adjacent etch lines of the standard gauge was 1 mm, the measuring precision of the gauge was 0.2 μm, the full scale range of the grating displacement measurement system was 200 mm, the left subsections were numbered from −100 mm to 0, the right subsections were numbered from 0 to 100 mm, and the normal measuring step was 10 mm. After the signal from the grating sensor was processed, the measuring system obtained a resolution of 1 μm. Considering the cost and some technical requirements of the instrument manufacturing, we let the value of the threshold be 4. Figure 2 shows the test results obtained by implementing the full scale method, the piece-wise subsection method, and the non-piece-wise error compensation method.

From Fig.2(a), it is seen that the error of the measuring system appears in a nonlinearly distributed pattern along two sides of the mark. Although the error changes slowly in the full scale range, the error sharply changes in the range from −20 to −40 mm and the spike errors in subsections from −20 to −30 mm and from −30 to −40 mm exceed the threshold value of 4. By computing the total error[8], we obtain the total error of ±5.5 μm. The measuring error curve shown in Fig. 2(b) represents an average test result measured 10 times by implementing the full scale method. It is seen that the measuring errors in many subsections are corrected and the total error is decreased to ±3.5 μm, but the spike error still exists. Figure 2(c) represents an average test result measured 10 times by implementing the piece-wise subsection correction method. It is seen that the measuring errors in most subsections are corrected and the total error is decreased to ±2.5 μm. The spike error becomes smaller but it still greatly influences the precision of the measuring system. Figure 2(d) shows a test result measured 10 times by implementing the non-piece-wise error compensation method without considering significant random errors.

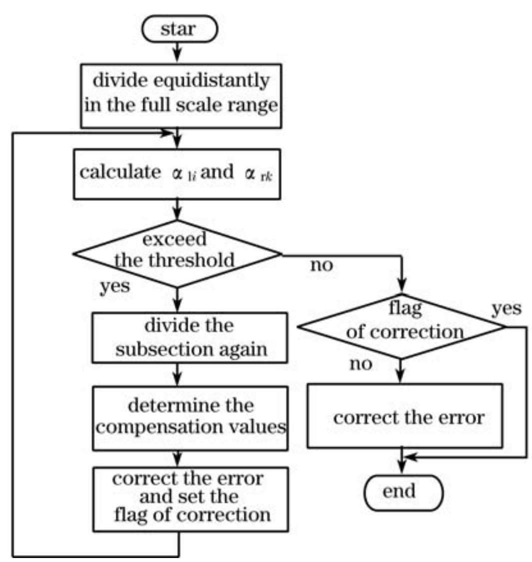

Fig. 1. Flow chart of non-piece-wise error compensation algorithm.

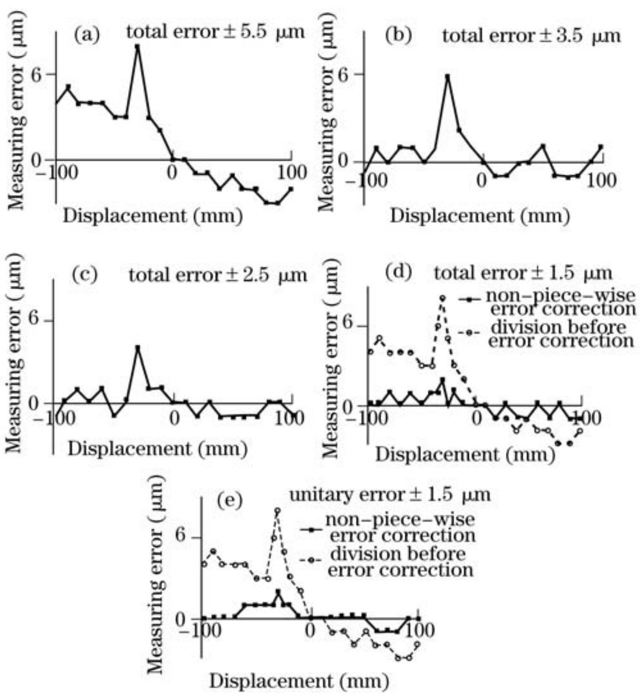

Fig. 2. Error testing results.

According to Eqs.(1) and (2), the subsection from −20 to −30 mm is subdivided into two subsections from −20 to −25 mm and from −25 to −30 mm, and the subsection from −30 to −40 mm is subdivided into two subsections similarly. It is seen that the error distribution in subsection from −20 to −30 mm is not proportional, which indicates that the same compensation parameter for the two redivided subsections could not effectively compensate the measuring errors. For the subsection from −30 to −40 mm, similar phenomenon is found. After different compensation parameters are obtained by the non-piece-wise error compensation method, the error compensation is implemented. It is seen that the spike error in the range from −20 to −40 mm is greatly decreased from 8 μm to 2 μm and the measuring errors in other subsections are less than 2 μm. Additionally, the whole error is significantly reduced by about 73%. Figure 2(e) shows a test result measured 30 times by implementing the non-piece-wise error compensation method considering significant random errors. Although the total error is still ± 1.5 μm, which is the same as the proposed method without considering significant random errors, the error compensated curve is smoother than the result obtained without considering significant random errors. The redivision has no influence on the error compensation for other subsections and the measuring error in other subsections can be compensated effectively. The test results indicate that the spike error compensation benefits from the redivision and the expected error compensated curve can be obtained by different compensation parameters and the weighted average values of the random errors.

In conclusion, a method for compensating the error of the grating displacement measurement system is presented. The full scale range is divided into piece-wise subsections and the redivision is determined by the comparison result. After obtaining different compensation parameters and the weighted average values of the random errors, the error compensation algorithm is implemented in the left and right subsections. Although the spike error occurs in some subsections and the error of the measuring system appears in a nonlinearly distributed pattern, the experimental results indicate that the proposed method may not only effectively compensate the spike error but also greatly improve the precision of the measuring system.

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