**Abstract:** The rapid progress of modern science and technology promotes the continuous development of precision measurement technology and improves the accuracy and efficiency of measuring instruments. In optical precision measurement technology, grating measurement technology has the advantage of high precision and large range. This study introduces the principle, structure and data handling of grating tester for dial indicator gauges. As the grating tester for dial indicator gauges is a kind of high precision measuring standard instrument, the verification basis, verification method and uncertainty analysis are also discussed in depth in this study.

1 **Introduction**

Measurement technology is closely related to the development of national economy, science and technology. With the rapid development of modern science and technology, higher requirements for measurement technology are raised. The accuracy and efficiency of measuring instruments have huge improvements since the appearance of new theories, new technologies and new methods. With the progress of science and technology and the development of production, the importance of precision measurement technology is becoming gradually remarkable, and the acquisition of precision measurement technology is becoming gradually important in all fields of the national economy and people's life. With the rapid development of microelectronics, optoelectronic technology and the maturity of laser, optical fiber, image processing and other related technologies, optical measurement technology has shown its own advantages, especially in high-precision measurement [1]. Optical measurement technology can achieve high precision, non-contact, real-time online, automatic and digital measurement. Optical measurement technology is being the basis of modern measurement technology. It is widely used because of its advantages of high accuracy, large range and anti-interference ability.

2 **Project system design**

We use handwheel to drive grating sensor moving a standard displacement, at the same time, use measuring rod to drive the indicator. When the indicator pointer get to the test point, stop and read the grating sensor standard displacement signal by computer, calculate the standard value and the indicated value to get the error of this verification point. Likewise, we complete the verification of all these points. Then, we handle the data according to the verification regulation and give the verification results by computer.

Grating tester for dial indicator gauges is composed of four parts: grating sensor, mechanical structure, grating signal acquisition and processing circuit, data processing software. Mechanical structure is used for fixing and installation of grating sensor, light source and indicator. Handwheel makes the grating sensor and the indicator a synchronous displacement. The grating sensor is composed of a main grating ruler, a side grating ruler and power supply. The relative motion of the main grating ruler and the side grating ruler makes the Moire fringe to a sinusoidal signal. The sinusoidal signal is converted to the digital pulse signal, which contains the displacement information by the pre-amplification, phase separation, shaping and electronic subdivision [2]. The data processing software is used for reading the digital pulse signal of grating and processing circuit and giving the parameters and conclusions according to the verification regulation.

2.1 **Grating sensor**

2.1.1 **Moire fringe:** The principle of grating sensor is Moire fringe. Moire fringe is an optical phenomenon firstly discovered by French researcher Moire in 18th century. The line space width of the fewer grating is equidistant, so they make the alternately dark and bright lines, as shown in Fig. 1. The diffraction effect of the more linear grating is so obvious that it cannot be explained by geometric optics. Their formation principle of Moire fringe must be explained by the diffraction phenomenon of grating. Moire fringe is the visual result of interference between two lines or objects at a constant angle and frequency. When the human eyes cannot distinguish the two lines or objects, only the patterns of interference are visible, the interference fringe is the Moire fringe. Therefore, the interference phenomenon can be simulated by Moire fringes [3].

2.1.2 **Grating measuring system:** Geometric measurement principle: The method of measurement is based on the geometrical optics principle of Moire fringe formation. When the angle is 0° and the fringe width is infinite, the two gratings move relative to each other. The two gratings open and close like a gate, and light and shade alter in the field of view. When two gratings move to each other a grid distance, light and shade change once. In the measurement system, two gratings are usually grating ruler and indicator grating. The grating ruler and the indicator grating produce Moire fringes by their relative motion. The distance of relative motion between the grating ruler and the indicator grating is detected by the variation period of the light energy of the fringe. This method is based on the principle of optical geometry measurement. When the grating lines are less, the grating system is based on the geometric measurement principle using the grating spacing as an unit.

![Fig. 1 Moire fringes](image-url)
screw are connected flexibly through the ball bearing to avoid the
shown in Figs. 2 and 3. The Moire fringe signal moves one period
other is the indicator grating. The diffraction light of the same level
direction of the lead screw. On the one hand, the horizontal
transmission mechanism, grating installation mechanism, grating
reading head installation mechanism and dial gauge clamp.
The base is the supportive structure, which is casted and then
machined. There is a V-groove on the base, which is used to install
the clamp. The precision guide rail is used for the installation of the
grating sensor base horizontally along the guide rail through the
screw, while the other end of the grating sensor base is fixed to the measuring rod. When the
gratings move a grating space relatively.

2.2 Mechanical structure
The mechanical part is horizontal structure which consists of base,
precision guide rail, manual rotating mechanism, precision
transmission mechanism, grating installation mechanism, grating
reading head installation mechanism and dial gauge clamp.

Interference measurement principle: When the grating spacing
is smaller as the wavelength of light, the diffraction fringes of the
gratinging is very obvious. The diffraction Moire fringes are formed by
the interference of diffraction beams. The diffraction Moire
fringes also need a pair of gratings. One is the grating ruler, the
other is the indicator grating. The diffraction light of the same level
is coherent light, and the interference field is infinity. The grating
makes the interference fringe on the focal plane by the lens [4], as
shown in Figs. 2 and 3. The Moire fringe signal moves one period
when the gratings move a grating space relatively.

2.3 Data handling
The dial gauge is fixed reliably on the clamp to ensure that the
measuring rod is in a horizontal direction. We execute the
verification after setting zero. In the positive direction, select the
individual interval and execute the whole verification. Then
compress the rod ten units and redo the verification of the negative
direction. During the whole verification process, the movement
direction of the rod cannot be changed, even any adjustment cannot
be made on the dial gauge and tester for dial indicator gauges.
The data processing can be done by using the macro processing
function in the Excel software. When the grating ruler collects the
displacement change, the measured displacement value can be
calculated by the analog-to-digital conversion circuit. The measured error can be subtracted from the nominal value by the
measured displacement value. A table is established to fill in the
effects read from the verification process and to complete the
calculation, as shown in Fig. 6. Take a dial gauge of 0.01 mm and
the range of 0–3 mm as an example. An Excel table is established by
the author for data processing. (C3: R3) is the error of the
positive direction in the range of 0–3 mm and (C4: R4) is the error
between the values in the adjacent 1 mm range and (C6: R6) is the error between
positive and negative direction of one point. These two rows of
data are calculated. C8 is the indication error in the full scale. C9 is
the indication error in any 1 mm range. C10 is the hysteresis error.
These three rows of data are the final verification results. They are
also calculated.

2.3.1 Full scale indication error: In the JTG35-2006 ‘dial gauges’
verification regulation, the indication error of the full scale is the
difference between the maximum value and the minimum value in the
error of all points. We use the MAX and MIN functions in
Excel to calculate the maximum and the minimum of the positive
direction, and then subtract them. We write them as a function:
MAX(C3: R3) – MIN(C3: R3), and fill the calculated results in the
C8 cell. This data is the final result of the indication error in the
full scale.

2.3.2 Indication error in any 1 mm range: In the verification
regulation, the indication error in any 1 mm range is determined by
the maximum difference between the maximum and the minimum
in any 1 mm range in the positive direction. First, we get the 1 mm
indication error in the range of 0–1 mm. The function is MAX(C3:
\[ H3) - \text{MIN}(C3: H3). \text{The result of the calculation is filled in the H5 cell. Then drag the mouse to the right of the H5 cell to get the indication error of all 1 mm ranges and calculate the maximum. The function is MAX(H5: R5)}. \text{The calculated result is filled in the C9 cell. This data is the indication error in any 1 mm range.} \]

2.3.3 **Hysteresis error:** In the verification regulation, the hysteresis error is the maximum of the difference of the points of the positive and negative direction. First, the difference between the positive and the negative direction of the first point shall be calculated. We calculate the absolute value of the difference between positive and negative direction errors of the first point by Excel ABS function. The function is \( \text{ABS(C3-C4)} \) and the result of calculation is filled in C10 cell. This data is the final result of hysteresis error.

According to JJG35-2006 ‘dial gauges’ verification regulation, only the above three errors which are qualified can be determined as qualified, otherwise, the dial gauge is unqualified. We can use the logic function \( \text{AND (C8 <= E8, C9 <= 9, C10 <= E10)} \) to determine the result and write the result to C12 cell. TRUE is OK and FALSE is NG [6].

According to the actual needs, we use grating sensor to produce standard displacement, collect verification or calibration data by computer, read the standard displacement of grating sensor, process the data and qualify judgement according to the requirements of regulation or specification. We can do the rapid verification of dial gauge, reduce the labour intensity and improve the efficiency through this project.

### 3 Verification

#### 3.1 Verification procedure

The verification regulation is JJG201-2008 ‘tester for dial indicator gauges’. The three bead table is installed on the measuring rod. The probe is installed in the holder hole and the holder is adjusted to align the probe to the centre of the three bead table. The grating tester for dial indicator gauges is pointed at the starting position of the selected measuring section. Then, the test is carried out according to the order of the measurement section from large to small. The verification of the subdivision measurement section should be carried out by selecting the section with the larger error in the previous measurement sections.

The gauge block with size of 1 mm is first placed on the three bead table. The probe is touched with the gauge block and set its indication value to zero. Then the gauge block is replaced according to the selected measuring interval. The handwheel or differential cylinder is rotated to the test point. Read out the error values of each point. The measurement should be carried out both on the positive and negative direction. After measuring the positive direction of each section of measurement, a further 10 units should be moved to the positive direction, and then the negative measurement should be carried out. No adjustment and moving direction of the rod should be changed. If it could not be tested in the whole measurement range once, it should be measured in sections and the error value should be accumulated [7].

#### 3.2 Uncertainty analysis

##### 3.2.1 Measurement method:

In accordance with the verification regulation, the tester for dial indicator gauges is calibrated by the inductance micrometer and the third class gauge block. It is expressed by the difference between the maximum value error and the minimum value error in the whole measuring range of the instrument.

\[ u' = u' (\varepsilon) = c_1 u (L_m) + c_2 u (L_0) + c_3 u (L_0) + c_4 u (\delta_0) + c_5 u (\delta_0) + c_6 u (\delta_0), \] (5)

##### 3.2.2 Mathematical model:

\[ e = L_m - (a + L_b - L_0) + L_0 \alpha_0 \Delta t_m + (L_b - L_0) \alpha_0 \Delta t_b, \] (1)

where \( e \) is the indication error of the measured point, \( L_m \) is the indication value of the measured point, \( a \) is the readings of the inductance micrometer at the measured point, \( L_b \), \( L_0 \) are the actual size of gauge blocks which are used for verification and zero adjustment, \( \alpha_0 \) are the coefficient of thermal expansion of the tester and the measuring block and \( \Delta t_m \), \( \Delta t_b \) are the temperature of the tester and the gauge block deviating from 20°C.

##### 3.2.3 Variance and sensitivity coefficient:

Suppose

\[ \delta_a = a_m - a_b, \quad \delta_b = \Delta t_m - \Delta t_b, \] (2)

\[ L = L_m - L_b - L_0, \quad \alpha = \alpha_0 = \alpha_b, \quad \Delta t = \Delta t_m = \Delta t_b, \] (3)

\[ e = L_m - (a + L_b - L_0) + L_0 \Delta t_0 \delta_0 + L_b \Delta t_0 \delta_0, \] (4)

(see (5))

\[ c_1 = \frac{\partial (e)}{\partial (L_m)} = \sqrt{3}, \] (6)

\[ c_2 = \frac{\partial (e)}{\partial (a_m)} = - \sqrt{2}, \] (7)

\[ c_3 = \frac{\partial (e)}{\partial (\Delta t_m)} = - \sqrt{2}, \] (8)

\[ c_4 = \frac{\partial (e)}{\partial (L_0)} = \sqrt{2}, \] (9)

\[ c_5 = \frac{\partial (e)}{\partial (\Delta t_b)} = \sqrt{2} L \cdot \Delta t, \] (10)

\[ c_6 = \frac{\partial (e)}{\partial (L_b)} = \sqrt{2} L \cdot a_0. \] (11)

##### 3.2.4 Evaluation of standard uncertainty:

\( u(L_m) \) is the uncertainty component introduced by the quantisation error of the instrument. Since the resolution of the instrument is greater than the measurement repeatability, the quantisation error of the instrument is introduced into the uncertainty component. The resolution of the instrument to be inspected is 0.2 μm, its quantisation error is 0.1 μm, and suppose if it is uniformly distributed in −0.1 μm to +0.1 μm interval, then:

\[ u(L_m) = 0.1 / \sqrt{3} = 0.06 \mu m. \] (12)

\( u(a) \) is the uncertainty component introduced by variability and indication error of inductance micrometer.

According to the verification regulation of JJG396-2002 ‘inductance micrometer’, the variability of indication value is 0.03 μm and the indication error is 0.08 μm in the range of 10 μm [8]. So, we choose the indication error which is bigger, suppose if it is uniformly distributed in −0.08 μm to +0.08 μm interval, then:

\[ u(a) = 0.08 / \sqrt{3} = 0.05 \mu m. \] (13)

\( u(L_m) \) is the uncertainty component introduced by central length of gauge block which is used for verification.

According to the verification regulation of JJG396-2011 ‘gauge block’, the measurement uncertainty of the central length of the third class gauge block is 0.11 μm, and the confidence probability is 99.7%, \( k = 3 \)

\[ u' (\varepsilon) = c_1 u (L_m) + c_2 u (L_0) + c_3 u (L_0) + c_4 u (\delta_0) + c_5 u (\delta_0) + c_6 u (\delta_0), \] (5)

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\[ L = 10 \text{ mm}, \ u(L_0) = 0.11/3 = 0.04 \mu m. \quad (14) \]

\( u(L_0) \) is the uncertainty component introduced by central length of gauge block which is used for zero adjustment.

Similarly, according to the verification regulation of JJG146-2011 ‘gauge block’, the measurement uncertainty of the central length of the third class gauge block is 0.11 \( \mu m \) [9], and the confidence probability is 99.7\%, \( k = 3 \), too

\[ L = 1 \text{ mm}, \ u(L_0) = 0.11/3 = 0.04 \mu m. \quad (15) \]

\( u(\delta_0) \) is the uncertainty component of the coefficient of thermal expansion between the instrument and the gauge block.

The coefficient of thermal expansion of the gauge block is \( \alpha = (11.5 \pm 1) \times 10^{-6} \degree C^{-1} \), and the difference between the glass thermal expansion coefficient of the grating ruler used in the instrument and the gauge block is \( \delta_0 = 6 \times 10^{-6} \degree C^{-1} \). Suppose it is uniformly distributed in \(-6 \times 10^{-6} \degree C^{-1} \) to \(+6 \times 10^{-6} \degree C^{-1} \) interval, then:

\[ u(\delta_0) = 6 \times 10^{-6}/\sqrt{3} = 3.46 \times 10^{-6} \degree C^{-1}. \quad (16) \]

\( u(\delta_0) \) is the uncertainty component of the temperature difference between the instrument and the gauge block.

The temperature difference between the instrument and the gauge block usually falls within \(-0.2 \degree C \) to \(+0.2 \degree C \) with equal probability. So it is uniformly distributed in \(-0.2 \degree C \) to \(+0.2 \degree C \) interval, then:

\[ u(\delta) = 0.2/\sqrt{3} = 0.12 \degree C. \quad (17) \]

3.2.5 Combined standard uncertainty and expanded uncertainty: Combined standard uncertainty:

\[ L = 10 \text{ mm}, \ u_c = \sqrt{0.08^2 + 0.07^2 + 0.06^2 + 0.06^2 + 0.1^2 + 0.02^2} = 0.17 \mu m. \quad (18) \]

Expanded uncertainty:

\[ U = ku_c = 0.34 \mu m \quad k = 2. \quad (19) \]

Conformance determination:

When \( L = 10 \text{ mm} \), the maximum permissible error value (MPEV) is 2 \( \mu m \) according the verification regulation of JG201-2008 ‘tester for dial indicator gauges’

\[ U \leq U_T = \frac{1}{3} \text{ MPEV}. \quad (20) \]

So the qualification criterion of measurement uncertainty is satisfied. The verification method is scientific, reasonable and feasible.

We also take a tester for dial indicator gauges of 10 mm range as an example. The original data record is shown in Fig. 7.

From the above data, the errors are less than the maximum permissible error values, we can judge that this tester for dial indicator gauges is qualified.

4 Conclusion

The advantages of grating measurement technology are high precision, low cost, wide range, strong anti-interference ability and easy to be miniaturised. The grating measurement is non-contact measurement and has no wear to the grating ruler, so it can keep the measuring accuracy of the grating ruler for a long time. The grating measuring system has the error average effect, so it can also improve the accuracy of measurement.

The application of grating is progressing with the development of grating manufacturing technology. With the continuous development of grating manufacturing technology and micro-processing technology, micro-optics research is more and more popular and the application of gratings is expanded. The optical grating technology is widely used in spectral analysis, metrology, quantum optics, integrated optics, optical communication, information processing and nanophase materials research which has attracted much attention of the world [10]. Meanwhile, the verification technology of the metrological instrument based on optical grating theory is getting more and more sustainable and is rapidly developing.

5 References

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