Research on calibration method of indication error of grade III standard metallic scale based on length measuring machine

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Abstract. A calibration method of indication error of grade III standard metallic scale based on length measuring machine is proposed. The existing length measuring machine is reformed to realize the calibration of the indication error of grade III standard metallic scale. According to the proposed calibration method, the evaluation model of measurement uncertainty is established, and the source of uncertainty is analysed. The expanded uncertainty is less than one third of the maximum permissible error specified in the verification regulation, which verifies the feasibility and effectiveness of the calibration method.

Keywords: Metrology; grade III standard metallic scale; length measuring machine; uncertainty in measurement.

1. Introduction

The grade III standard metallic scale is mostly used to verify the level ruler, steel ruler and other line scale[1]. Common grade III standard metallic scale materials include zinc, white copper, stainless steel, brass, etc. The grade III standard metallic scale is a rigid ruler, and its scribed line is on two inclined planes at an angle of 45° to the bottom. 1020mm scribed lines are engraved on both sides, of which the division value of one side is 0.2 mm and the other side is 1 mm. The verification regulation of JJG71-2005 standard metallic scale (Grade III) requires that the maximum permissible error of indication is ± $(0.03 + 0.02L)$ mm. The verification method of indication error can be verified by laser interferometer or grade II standard metallic scale as standard ruler on length measuring machine or other verification devices. According to the requirements of verification regulations, reference[2] installed a grade II standard metallic scale on a one meter length measuring machine to carry out verification, and analyzed its measurement uncertainty. In reference [3], the measurement accuracy factors of two indication error verification methods in the verification regulation was discussed. The research shows that the laboratory ambient temperature and the flatness of the bottom of the third-order linear ruler are important factors for the measurement accuracy. In reference [4], the author proposed a method to verify grade III standard metallic scale with MLD one meter measuring machine, and analyzed its measurement uncertainty. In this paper, a method of directly using the length measuring machine to verify the indication error of grade III standard metallic scale is proposed, and the influence of the temperature in the measurement process, the Abbe error of the device and the inclination error of the reading device are corrected to improve the measurement accuracy, and the measurement uncertainty is analyzed. The expanded uncertainty result of the indication error meets the requirements of the maximum permissible error of the verification regulation.

2. Calibration method

The grade III standard metallic scale indication error verification device based on the length measuring machine is transformed from the existing length measuring machine, as shown in Figure 1. A fixed support of the scale with two-way micro adjustment is designed near the track axis of the length measuring machine to realize the fixation and position fine adjustment of the scale. The distance between the two fixed supports is equal to the distance of the Bessel support point of the grade III standard metallic scale. A reading device which can read the linear scale of the scale is installed on the tailstock of the length measuring machine, and an attached thermometer is installed on the track of the length measuring machine and the scale to realize the real-time temperature measurement of the length measuring machine and the tested scale.

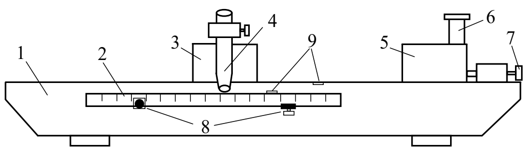

Fig. 1 Schematic diagram of grade III standard metallic scale indication error verification device

1 – length measuring machine; 2 – grade III standard metallic scale; 3 – tailstock; 4 –micro reading device; 5 – measuring seat; 6 – microscope; 7 – adjustment handwheel; 8 – adjustment of the scale; 9 – thermometer

The verification process of the indication error of the grade III standard metallic scale based on the length measuring machine is similar to that in part 6.3.8.2 of JJG71-2005 standard metallic scale (Grade III). The main difference is that this method takes the actual length of the length measuring machine as the standard length. At the same time, because the axis of the length measuring machine is different from the axis of the scale, it does not comply with the Abbe principle, and Abbe error correction is required during measurement data processing. The Abbe error calculation method is as follows: firstly, use the autocollimator to measure the straightness runout angle of the length measuring machine track in the horizontal and vertical directions at the tested interval, and multiply this angle by the distance between the length measuring machine track and the tested scale to obtain the Abbe error in the corresponding direction. In addition, due to the influence of the flatness of the engraving surface of grade III standard metallic scale, the error will be introduced when there is an inclination error of the optical axis of the micro reading device, so it also needs to be corrected.

3. Evaluation of measurement uncertainty

3.1 Measurement model

According to the calibration method, the measurement model of indication error of grade III standard metallic scale based on length measuring machine is

$$L_x = L_s - \Delta L_x + (\alpha_s \delta t_s - \alpha_x \delta t_x)L + \delta l_a + \delta l_b \quad (1)$$

Where L_x is actual length of grade III standard metallic scale, L_s is actual length of the length measuring machine at the inspected interval, ΔL_x is measured deviation of the tested interval of the grade III standard metallic scale, α_s is linear expansion coefficient of length measuring machine, δt_x is deviation between the average temperature of the length measuring machine and the reference temperature of 20℃, α_x is linear expansion coefficient of grade III standard metallic scale, δt_s is deviation between the average temperature of the grade III standard metallic scale and the reference temperature of 20℃, L is nominal length of the tested interval of the scale, δl_a is Abbe error between grade III standard metallic scale and length measuring machine, δl_b is optical axis inclination error of micro reading device.

Because each component is independent of each other, the combined standard uncertainty is calculated by the following formula[5]

$$u_c^2(L_x) = c_1^2 u^2(L_s) + c_2^2 u^2(\Delta L_x) + c_3^2 u^2(\alpha_s) + c_4^2 u^2(\delta t_s) + c_5^2 u^2(\alpha_x) + c_6^2 u(\delta t_x) + c_7^2 u^2(\delta l_a) + c_8^2 u(\delta l_b) \quad (2)$$

Where coefficient of sensitivity c_1 is equal to 1, c_2 is equal to -1, c_3 is equal to $\delta t_s L$, c_4 is equal to $\alpha_s L$, c_5 is equal to -$\delta t_x L$, c_6 is equal to -$\alpha_x L$, c_7 is equal to 1, c_8 is equal to 1. During the actual measurement, the scale and the length measuring machine are fully isothermal, and the actual measurement temperature is about 21.0℃, so δt_s and δt_x are both equal 1.0℃. According to the materials of the grade III standard metallic scale and length measuring machine, α_s is 11.5×10-6℃, α_x is 10.8×10-6℃.

3.2 Calculation of standard uncertainty

3.2.1 Calculation of u(Ls)

Expanded uncertainty of indication error of micrometer scale of length measuring machine U is 0.3μm+2.1×10^{-6}L (k=2), then the uncertainty component $u(L_s)$ is

$$u(L_s) = \frac{(0.3\mu m + 2.1\times10^{-6}L)}{2} = 0.15\mu m + 1.05\times10^{-6}L \quad (3)$$

3.2.2 Calculation of u(ΔLx)

Uncertainty component $u(\Delta L_x)$ introduced by measuring the actual length deviation of the tested ruler is mainly introduced for measurement repeatability. Carry out 10 times repeated alignment measurements on 100mm scribed lines, and the calculated experimental standard deviation s of a single reading is 1.91μm. according to the verification regulation JJG71-2005[1], the indication error of the tested interval is the reading difference between the tested scribed line and the zero scribed line. It is necessary to carry out two times measurements, that is, the average value of the four measured values. Then the uncertainty component $u(\Delta L_x)$ introduced by the actual length deviation measurement of the tested ruler is

$$u(\Delta L_x) = \frac{\sqrt{2}\times1.91\mu m}{\sqrt{4}} = 1.35\mu m \quad (4)$$

3.2.3 Calculation of u(αs)

The linear expansion coefficient of the length measuring machine shall be (11.5±1)×10-^{6}℃$^{-1}$, the half width range is 1×10^{-6}℃$^{-1}$, estimated by uniform distribution, uncertainty component $u(\alpha_s)$ introduced by linear expansion coefficient of the length measuring machines is

$$u(\alpha_s) = \frac{1\times10^{-6}℃^{-1}}{\sqrt{3}} = 0.577\times10^{-6}℃^{-1} \quad (5)$$

3.2.4 Calculation of u(Δts)

The average temperature of the length measuring machine is the average value of the starting temperature and the ending temperature of each measured return. The instrument used is an attached thermometer, and its MPE is ±0.2℃. If it is estimated by uniform distribution, then the uncertainty component $u(\Delta t_s)$ introduced by the average temperature deviation of the length measuring machine is

$$u(\Delta t_s)=\frac{\sqrt{4}\times 0.2℃}{\sqrt{3}}=0.23℃ \quad (6)$$

3.2.5 Calculation of u(αx)

The tested ruler coefficient of the length measuring machine shall be (10.8±1)×10^-6^℃^-1^, the half width range is 1×10^-6^℃^-1^, estimated by uniform distribution, uncertainty component $u(\alpha_x)$ introduced by linear expansion coefficient of the tested ruler is

$$u(\alpha_x)=\frac{1\times10^{-6}℃^{-1}}{\sqrt{3}}=0.577\times10^{-6}℃^{-1} \quad (7)$$

3.2.6 Calculation of u(Δtx)

The average temperature of the tested ruler is the average value of the starting temperature and the ending temperature of each measured return. The instrument used is an attached thermometer, and its MPE is ±0.2℃. If it is estimated by uniform distribution, then the uncertainty component $u(\Delta t_s)$ introduced by the average temperature deviation of the tested ruler is

$$u(\Delta t_x)=\frac{\sqrt{4}\times 0.2℃}{\sqrt{3}}=0.23℃ \quad (8)$$

3.2.7 Calculation of u(δla)

Because the tested ruler and the length measuring machine are parallel longitudinal measurement, this method does not conform to Abbe principle, and Abbe error compensation is required during measurement. The Abbe error δl_a is calculated by the following

$$\delta l_a = d_H\varphi_H + d_V\varphi_V \quad (9)$$

Where d_H is the horizontal distance between the axis of the tested ruler and the axis of the length measuring machine, φ_H is the horizontal angle between the guide rail of the length measuring machine at the inspected point and its ideal axis, d_V is the vertical distance between the axis of the tested ruler and the axis of the length measuring machine, φ_V is the vertical clamping angle between the guide rail of the length measuring machine at the inspected point and its ideal axis.

Then the uncertainty component $u(\delta l_a)$ caused by Abbe error between the tested ruler and the length measuring machine is

$$u^2(\delta l_a)=d_H^2\times u^2(\varphi_H)+\varphi_H^2\times u^2(d_H)+d_V^2\times u^2(\varphi_V)+\varphi_V^2\times u^2(d_V) \quad (10)$$

During actual measurement, the distance between the axis of the tested ruler and the axis of the length measuring machine measured with a steel ruler in the horizontal direction is 190mm, and the distance in the vertical direction is 175mm. The expanded uncertainty of distance measurement is U=5mm(k=2). Then there are

$$u(d_H)=u(d_V)=\frac{5\text{mm}}{2}=2.5\text{mm} \quad (11)$$

The maximum horizontal angle between the length measuring machine guide rail and its ideal axis measured by the autocollimator is 4.8×10^{-5}rad, the maximum included angle in the vertical direction is 1.5×10^{-4}rad, expanded uncertainty of included angle measurement is $U=1.0\times10^{-5}$rad(k=2). Then there are

$$u(\varphi_H)=u(\varphi_V)=\frac{1.0\times10^{-5}\text{rad}}{2}=5.0\times10^{-6}\text{rad} \quad (12)$$

Then the uncertainty component $u(\delta l_a)$ caused by Abbe error between the tested ruler and the length measuring machine is

$$u(\delta l_a)=1.30\mu\text{m} \quad (13)$$

3.2.8 Calculation of u(δlb)

When there is deflection deformation on the surface of the tested ruler, and the optical axis of the reading device is not perpendicular to the surface of the tested line, the inclination error will affect the measurement results. Optical axis inclination error of reading device δl_b is calculated as

$$\delta l_b = r\times\varphi_G \quad (14)$$

In the actual measurement, the deflection r of grade III standard metallic scale is taken as 0.2mm, and the expanded uncertainty of the measurement of the included angle between the optical axis and the normal direction of the inspected line surface is $U=2.91\times10^{-3}$rad(k=2). Then the $u(\delta l_b)$ is

$$u(\delta l_b)=0.2\text{mm}\times10^3\times\frac{2.91\times10^{-3}\text{rad}}{2}=0.29\mu\text{m} \quad (15)$$

3.3 Combined standard uncertainty

3.3.1 The calculation results of standard uncertainty

The source of standard uncertainty components of measurement results is shown in Table 1.

Tab.le 1. The source of standard uncertainty components of measurement results

$u(x_i)$	The source of standard uncertainty	coefficient of sensitivity c_i	results of $u(x_i)$
$u(L_s)$	The uncertainty introduced by the length measuring machine in the actual length measurement of the inspected interval	1	0.15μm+ $1.05\times10^{-6}L$
$u(\Delta L_x)$	The uncertainty introduced by the tested ruler in the actual length measurement of the inspected interval	-1	1.35μm
$u(\alpha_s)$	Uncertainty introduced by linear expansion coefficient of length measuring machine	1.0℃×L	0.577×10^{-6}℃$^{-1}$

$u(\delta t_s)$	Uncertainty introduced in the measurement of average temperature deviation of length measuring machine	11.5×10^{-6}°C ×L	0.23°C
$u(\alpha_x)$	Uncertainty introduced by linear expansion coefficient of the tested ruler	-1.0°C×L	0.577×10^{-6}°C^{-1}
$u(\delta t_x)$	Uncertainty introduced by the measurement of the average temperature deviation of the tested ruler	10.8×10^{-6}°C ×L	0.23°C
$u(\delta l_a)$	Uncertainty caused by Abbe error between the measured ruler and the length measuring machine	1	1.30μm
$u(\delta l_b)$	Uncertainty introduced by optical axis inclination error of reading device	1	0.29μm

3.3.2 The calculation results of combined standard uncertainty

According to formula (2), the combined standard uncertainty of different tested intervals can be calculated, and the results are shown in Table 2.

Table 2. The combined standard uncertainty of different tested intervals

tested intervals (mm)	0	100	200	300	400	500	600	700	800	900	1000
$c_1\times u(L_s)$ (μm)	0.15	0.26	0.36	0.47	0.57	0.68	0.78	0.89	0.99	1.10	1.20
$c_2\times u(\Delta L_x)$ (μm)	-1.35	-1.35	-1.35	-1.35	-1.35	-1.35	-1.35	-1.35	-1.35	-1.35	-1.35
$c_3\times u(\alpha_s)$ (μm)	0.00	0.06	0.12	0.17	0.23	0.29	0.35	0.40	0.46	0.52	0.58
$c_4\times u(\delta t_s)$ (μm)	0.00	0.26	0.53	0.79	1.06	1.32	1.59	1.85	2.12	2.38	2.65
$c_5\times u(\alpha_x)$ (μm)	0.00	0.06	0.12	0.17	0.23	0.29	0.35	0.40	0.46	0.52	0.58
$c_6\times u(\delta t_x)$ (μm)	0.00	0.25	0.50	0.75	0.99	1.24	1.49	1.74	1.99	2.24	2.48
$c_7\times u(\delta l_a)$ (μm)	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
$c_8\times u(\delta l_b)$ (μm)	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
$u_c(L_x)$ (μm)	1.90	1.95	2.07	2.25	2.48	2.74	3.03	3.34	3.66	4.00	4.34

Linearize uc(Lx) in Table 2 to obtain

$$u_c(L_x)=1.9\mu\text{m}+2.5\times10^{-6}L \tag{16}$$

3.4 Expanded uncertainty

Taking the inclusion factor k=2, the expanded uncertainty of the indication error measurement of grade III standard metallic scale is

$$U=k\times u_c(L_x)=3.8\mu\text{m}+5.0\times10^{-6}L \tag{17}$$

4. Summary

By reforming the existing length measuring machine and considering the influence of temperature compensation and Abbe error correction during calibration, the calibration of the indication error of grade III standard metallic scale can be realized. The expanded uncertainty of indication error is less than one third of the maximum allowable error of indication required by the verification regulation, which indicates that the method in this paper is effective and feasible.

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