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## Peculiarities of Measurement Uncertainty Evaluation At Calibrating a Ring Gauge

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**Abstract.** Example S13 from EA-4/02 M:2013 “Calibration of a ring gauge with a nominal diameter of 90 mm” is analyzed. The report uses the kurtosis method and the law of propagation of expanded uncertainty developed by the authors to the expanded uncertainty evaluation. It is shown that the introduction of a coaxiality correction for the ring gauge and the measuring axis of the comparator leads to the need to estimate its standard measurement uncertainty using the second-order terms of the Taylor series and taking into account the kurtosis of input quantities using the method of partial increments. A good agreement between the results obtained by applying the described procedure and the results obtained by the Monte Carlo method is shown.

**Keywords:** Measurement Uncertainty, Kurtosis Method, Calibration, Ring Gauge

### 1. Introduction

Standard ISO 17025-2017 [1] (sec. 7.8.6) provides for the possibility of introducing into the calibration certificate of a measuring instrument (MI) the decision whether a calibrated MI is in compliance with metrological requirements. This decision must be made taking into account the expanded measurement uncertainty [2]. Therefore, the level of risk (for example, a false positive or false negative decision) related to an applied compliance decision rule will depend on the precision of the expanded uncertainty evaluation [1], 7.8.6.1. A reliable estimate of the expanded uncertainty cannot be obtained without taking into account the laws of distribution of input quantities [3], which is usually done by the Monte Carlo method (MCM) [4]. To solve this problem, the authors proposed the kurtosis method (KM) and expanded uncertainty propagation law (EUPL) [5]. Their application makes it possible to automate the uncertainty calculation, while the estimates of the expanded uncertainty will be close to the estimates obtained by the MCM. Supplement 2 of document EA-4/02 M:2013 [6] considers examples for situations where the measurement uncertainty budget is dominated by one or two abnormal contributions, which makes it impossible to use the coverage factor  $k=2$  when expanded uncertainty evaluation. For examples S9-S12, the application of the kurtosis method was considered by the authors in [3, 7]. Below we will consider the use of the proposed methods for measurement uncertainty evaluation at calibration of a ring gauge (example S13 from Supplement 2 [6]).

### 2. Subject and Methods

The diameter  $d_X$  of the ring to be calibrated at the reference temperature is obtained from the relationship S13.1 [6]:

$$d_X = d_S + \Delta l + \delta l_i + \delta l_T + \delta l_P + \delta l_E + \delta l_A,$$

where  $d_X$  is diameter of the reference setting ring at the reference temperature,  $\Delta l$  is observed difference in displacement of the measuring spindle when the contact tips touch the inner surface of the rings at two diametrically apart points;  $\delta l_i$  is correction for the errors of indication of the comparator;  $\delta l_T$  is correction due to the temperature effects of the ring to be calibrated, the reference setting ring and the comparator line scale;  $\delta l_P$  is correction due to coaxial misalignment of the probes with respect to the

measuring line;  $\delta l_E$  is correction due to the difference in elastic deformations of the ring to be calibrated and the reference setting ring,  $\delta l_A$  is correction due to the difference of the Abbe errors of the comparator when the diameters of the ring to be calibrated and the reference setting ring are measured.

Since the quantity  $\Delta l$  is measured by carrying out  $n$  repeated measurements, taking into account the recommendations of [8], this expression should be rewritten as:

$$d_x = d_s + (\Delta l + \varepsilon_{\Delta l}) + \delta l_i + \delta l_T + \delta l_p + \delta l_E + \delta l_A, \quad (1)$$

where  $\varepsilon_{\Delta l}$  is correction for a random error, the value of which  $\hat{\varepsilon}_{\Delta l} = 0$  and the standard uncertainty is determined by the formula [5]:

$$u(\varepsilon_{\Delta l}) = \sqrt{\frac{1}{n(n-1)} \sum_{q=1}^n (\Delta l_q - \overline{\Delta l})^2} \sqrt{\frac{n-1}{n-3}}, \quad (2)$$

and  $\overline{\Delta l}$  is estimated as the arithmetic mean of repeated measurements:

$$\overline{\Delta l} = \frac{1}{n} \sum_{q=1}^n \Delta l_q. \quad (3)$$

To improve the accuracy of the calculations, the standard uncertainties of the input quantities were refined based on the data given in example S13 [6]. For the results of five-time measurements of  $\Delta l$  given in S13.9 [6],  $\overline{\Delta l} = 49.999536$  mm and  $u(\varepsilon_{\Delta l}) = 0.2073$   $\mu\text{m}$ . With this quantity  $\Delta l$ , we attribute the standard uncertainty  $u(\Delta l) = 0.2898$   $\mu\text{m}$ , associated with the zero setting of the comparator readings, which was determined a priori. Standard uncertainties  $u(\delta l_i)$ ,  $u(\delta l_E)$ , and  $u(\delta l_A)$  calculated with accurate to fourth significant digit. Therefore,  $u(d_x)$  will be equal to 0.4048  $\mu\text{m}$  (Table 1) and not 0.433 as in S13.10 [6].

Table 1. Refined Measurement Uncertainty Budget S13.10 [6]

$X_i$	$x_i$	$u(x_i)$	PDF	$c_i$	$u_i(y)$
$d_s$	40,000 7 mm	0,10 $\mu\text{m}$	normal	1,0	0,10 $\mu\text{m}$
$\Delta l$	49,999 536 mm	0,2898 $\mu\text{m}$	normal	1,0	0,2898 $\mu\text{m}$
$\delta l_i$	0,0 mm	0,2165 $\mu\text{m}$	rectangular	1,0	0,2165 $\mu\text{m}$
$\delta l_T$	0,0 mm	0,15 $\mu\text{m}$	normal	1,0	0,15 $\mu\text{m}$
$\delta l_p$	0,000 004 mm	0,0065 $\mu\text{m}$	rectangular	1,0	0,0065 $\mu\text{m}$
$\delta l_E$	0,0 mm	0,01732 $\mu\text{m}$	rectangular	1,0	0,01732 $\mu\text{m}$
$\delta l_A$	0,0 mm	0,01154 $\mu\text{m}$	rectangular	1,0	0,01154 $\mu\text{m}$
$Y$	$y$	$u(y)$	$p$	$k$	$U$
$d_x$	90,000 24 mm	0,4048 $\mu\text{m}$	0,9545	2	0,8095 $\mu\text{m}$

Thus, the expanded uncertainty for the confidence level  $p = 0.9545$  is  $2 \cdot 0.4048 = 0.81$   $\mu\text{m}$ . For  $p = 0.95$ , it will be, respectively,  $1.96 \cdot 0.4048 = 0.79$   $\mu\text{m}$ .

Uncertainty budgets constructed in accordance with the EUPL for the confidence level  $p = 0.9545$  are presented in Table 2 and 3. Expanded uncertainty in Table 2 was calculated by the kurtosis method [5] according to the formula

$$U_B = k \cdot u_B(d_x), \quad (4)$$

in which the coverage factor depending on the level of confidence  $p$  was calculated as:

$$k_B = \begin{cases} 0,1085\eta_B^3 + 0,1\eta_B + 1,96, & \text{for } p = 0,95; \\ 0,12\eta_B^3 + 0,1\eta_B + 2, & \text{for } p = 0,9545, \end{cases} \quad (5)$$

where  $\eta_B$  is the kurtosis of the measurand, calculated according to the data in Table 2.

Table 2. Measurement Uncertainty Budget for Type B Components

$X_i$	$x_i$	$u(x_i)$	$\eta(x_i)$	$c_i$	$u_i(y)$
$d_S$	40,000 7 mm	0,10 $\mu\text{m}$	0	1,0	0,10 $\mu\text{m}$
$\Delta l$	49,999 536 mm	0,25 $\mu\text{m}$	0	1,0	0,25 $\mu\text{m}$
$\delta l_i$	0,0 mm	0,2165 $\mu\text{m}$	-1,2	1,0	0,2165 $\mu\text{m}$
$\delta l_T$	0,0 mm	0,15 $\mu\text{m}$	0	1,0	0,15 $\mu\text{m}$
$\delta l_P$	0,000 004 mm	0,0065 $\mu\text{m}$	-1,2	1,0	0,0065 $\mu\text{m}$
$\delta l_E$	0,0 mm	0,01732 $\mu\text{m}$	-1,2	1,0	0,01732 $\mu\text{m}$
$\delta l_A$	0,0 mm	0,01154 $\mu\text{m}$	-1,2	1,0	0,01154 $\mu\text{m}$
$Y$	$y$	$u_B(y)$	$\eta(y)$	$k$	$U_B$
$d_X$	90,000 24 mm	0,3773 $\mu\text{m}$	-0,105	1,989	0,7506 $\mu\text{m}$

Table 3. Measurement Uncertainty Budget for Random Errors

$X_i$	$x_i$	$u(x_i)$	$v_i$	$c_i$	$u_i(y)$
$\varepsilon_{\Delta l}$	0	0,2073 $\mu\text{m}$	4	1	0,2073 $\mu\text{m}$
$Y$	$\hat{\varepsilon}$	$u_A(\hat{\varepsilon})$	$p$	$t_{p,(n-1)}$	$U_A$
$\varepsilon$	0	0,2073 $\mu\text{m}$	0,9545	2,869	0,4206 $\mu\text{m}$

Expanded uncertainty  $U_A$  in Table 3, was calculated by EUPL [5] using the formula:

$$U_A = t_{p,(n-1)} \cdot c \cdot u(\varepsilon_{\Delta l}) \sqrt{(n-3)/(n-1)}, \quad (6)$$

where  $t_{p,(n-1)}$  is the Student's coefficient for the probability  $p$  and the number of degrees of freedom  $v = n - 1$ . The total expanded measurement uncertainty will be calculated using the formula [5]:

$$U(d_x) = \sqrt{U_B^2 + U_A^2}. \quad (7)$$

From the data given in tables 2,3 them, in accordance with the EUPL, we have a standard uncertainty of 0.43  $\mu\text{m}$  and an expanded uncertainty of 0.86  $\mu\text{m}$  for  $p=0.9545$  and 0.84  $\mu\text{m}$  for  $p=0.95$ .

An estimate of the measurement uncertainty by the Monte Carlo method is obtained using the program [9]. The combined standard and expanded measurement uncertainties for  $p=0.95$  are 0.43  $\mu\text{m}$  and 0.8365  $\mu\text{m}$ , respectively. Comparison of the results obtained by various methods is given in table. 4

Table 4. Calculation results obtained by different methods

Method	$y$	$u(y)$	$U$	$k$
EA-4/02	90,00024	0,4048	0,7933	1,96
EUPL	90,00024	0,4305	0,8406	1,953
MMC	90,00026	0,43	0,837	1,947

When calibrating a ring gauge with a length comparator, a specific error occurs due to misalignment between the ring gauge and the measuring axis of the comparator (Fig. 1). The chord length  $d_1$  observed during the measurement is related to the diameter of the ring  $d$  by the following relation:

$$\frac{d}{2} = \sqrt{\left(\frac{d_1}{2}\right)^2 + \delta_c^2} = \frac{d_1}{2} \sqrt{1 + \frac{4\delta_c^2}{(d_1)^2}} \approx \frac{d_1}{2} + \frac{\delta_c^2}{D}, \quad (8)$$

where  $D$  is the nominal value of the ring diameter.

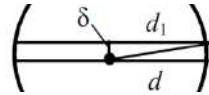


Fig.1. Misalignment of the ring gauge and the measuring axis of the comparator

Using the method of partial increments, we get:

$$\Delta d = \hat{d} - \hat{d}_1 = 2 \{ [\hat{\delta} + u(\hat{\delta})]^2 + [\hat{\delta} - u(\hat{\delta})]^2 \} / 2D = 2[\hat{\delta} + u(\hat{\delta})]^2 / D, \quad (9)$$

those the estimate  $d$  for  $\hat{\delta}_c = 0$  will be equal to:

$$\Delta d = 2u^2(\hat{\delta}) / D. \quad (10)$$

Expression for unbiased estimate of the measurand derived from recommendations [6]:

$$u(\Delta d) = 2u^2(\delta) \sqrt{\eta(\delta) + 2} / D = \Delta d \sqrt{\eta(\delta) + 2}. \quad (11)$$

For the given in [6] values:  $D_x = 90$  mm,  $\delta = \pm 20$   $\mu\text{m}$ , and the uniform PDF of  $\delta$ , we have  $u(\delta) = 11.5$   $\mu\text{m}$ ,  $\eta(\delta) = -1.2$ , and we obtain  $\Delta d = 0.003$   $\mu\text{m}$  and  $u(\Delta d) = 0.0027$   $\mu\text{m}$ .

### 3. Results

Measurement uncertainty evaluation at calibrating of ring gauge with an Abbe comparator is considered based on the approaches outlined in the COOMET R/GM/35:2022 recommendation: the kurtosis method, the law of propagation of expanded uncertainty, the method of partial increments, the method of finding the bias of the estimate of the standard uncertainty of the measurand for a nonlinear model with taking into account the kurtosis of input quantities. The measurement uncertainty estimate obtained using the MCM differs by 1% from the estimate by the proposed methods and by 6% from the estimate obtained by the [6].

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