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Thread Gauge Calibration for Industrial Applications

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There are two most commonly used methods for calibration of thread rings, with different measuring uncertainty. The method of mechanical sensing with two balls is mostly used on one-axial measuring machines and on coordinate measuring machines. However, the method of calculating the core diameter of the thread ring combined with the technique of adaptation (in accordance with the method of the smallest squares) is used on the profile scanner.

The required tolerances, which are very narrow for adjustable and laboratory thread ring, so the measuring uncertainty may be too high when using the method of mechanical sensing with two balls, and the low quality of some control rings, are the decisive factors for choosing an appropriate method in the industry. This also depends on the laboratory's capability of executing a specific method.

The measurements of the core diameter of thread rings, which are the main topic of this article, were included into an international inter-comparison in which the main subject was the same thread ring as the one mentioned in this article.

Keywords: thread ring gauge, calibration, pitch diameter, measurement uncertainty, dimensional measurements

0 INTRODUCTION

Calibration of thread gauges has always been the domain of metrologists, who calibrate length. If determining inner measurements of smooth hollow objects is a much more difficult task than determining the diameter of cylinder (plug gauges etc.), then this claim is more valid for determining measurements of inner threads. In numerous cases, people used to help themselves by pouring liquid metal, sulphur or paraffin wax or other appropriate mixtures in the nut, and then unscrew the core from the nut and measure it. Later on, more precise calibration types were developed, where the thread ring did not require cutting, but different devices to check the diameter of the thread. They used different calibers for threads and also devices, which resemble today's universal length device. Berndt already describes calibration in his book Gewinde [1], which is very similar to today's calibration on 1-D measuring machine.

There are a few methods how to calibrate thread plug gauges also used in industry, but only classical methods, such as the two balls method, are used for calibration of thread ring gauges. Those classical methods have been well known since the 19th century and are executed by means of universal measuring machines [1], and in the last two decades even by means of coordinate measuring machines while more modern methods, used in some laboratories in Europe, deal with scanning the profile and mathematical processing of the received data. These methods are executed on optical as well as on mechanical scanning machines.

In the past years, a lot of comparison studies of thread gauges calibrations were made by dimensional laboratories in Europe. There were no great deviations in measurements of thread plug calibrations, but many in measurements of thread ring gauge calibrations. The obtained results were different, which means that the calibration results obtained from different machines of individual laboratories did not match.

By comparing calibrations of the thread ring gauge performed with different methods and by changing the influences of an individual method as well as statistical processing of the gained results, the impact of the influences on the uncertainty of the calibration of the thread ring pitch diameter could be reduced. The most common influence is form deviation, and there is an influence of the mechanics of the measuring machine as well as mechanical probing by means

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of the machine, which are considered to be less controllable. The guidance for accreditation of the procedure and the calculation of the measuring uncertainty of all calibration types is the Euramet document EURAMET/cg-10/v.01 [2].

1 THREAD RING CALIBRATIONS

1.1 Definition of Thread Ring

If a point travels in a circle and at the same time performs a vertical move up or down, which is proportional to the individual rotation angle, then this point describes a thread. The easiest way of obtaining such a thread is to wind up a rectangular triangle around a round cylinder (with a diameter *d*), while the baseline of the triangle should be equal to the circumference of the cylinder ($d \cdot \pi$) – in this way its hypotenuse represents the screws line.

The cylinder, which is equipped with a thread, represents the bolt; however, should the inner side of the cylinder be equipped with a thread, then it represents a ring.

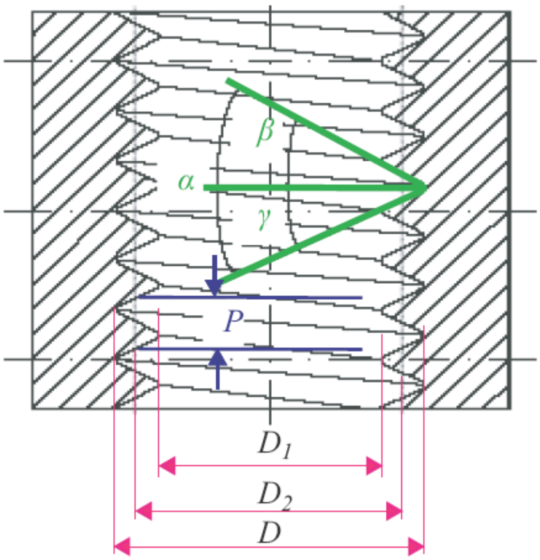

Fig. 1. *The main parameters of thread ring*

The main parameters of a thread ring are: the maximum diameter (D), the minimum diameter (D_1), the pitch (P), the flank angles (β, γ), thread angle (α), where $\alpha = \beta + \gamma$, the lead angle (ψ), the pitch diameter (D_2).

1.2 Thread Ring Calibration Categories

As mentioned above, two different methods to calibrate thread rings were used. The first method is a classical two balls method and the second is mechanical scanning of the profile with mathematical processing of the received data. In [2], several categories of thread ring calibration are introduced. These categories are:

- measurement of the diameter,
- measurement of diameter and pitch,
- measurement of the 2D axial profile.

In this article both methods of calibration and three different categories are compared.

1.2.1 Measurement of the Diameter

The pitch diameter D_2 of a thread is calculated from the measured value ΔL, for which the rake and the measurement force must be corrected, and from the assumed nominal values of the pitch and the angle of the thread.

1.2.2 Measurement of Diameter and Pitch

The pitch diameter D_2 of a thread is calculated from the measured value ΔL and the measured pitch P, for which the rake and the measurement force must be corrected, and from the assumed nominal values of the distance and the angle of the thread.

1.2.3 Measurement of the 2D Axial Profile

The measurement of the whole profile allows a much more precise characterization of the thread as if measuring only its certain points, because the profile of the thread ring is scanned and the desired parameters are mathematically calculated.

1.2.4 Implementation of Each Category

The compared categories of thread ring calibration are implemented on:

- 1-D measuring machine [3] (category *1.2.1*, Fig. 2),
- coordinate measuring machine (CMM) [4] (category *1.2.2*, Fig. 3),
- profile scanner [5] and [6] (category *1.2.3*, Fig. 4),

which have one common calibration category; the measurement of medium thread diameter (category *1.2.1*), therefore this research is limited to a comparison of results solely in this category as in Slovenia this category of calibration of thread rings meets a big part of the industry.

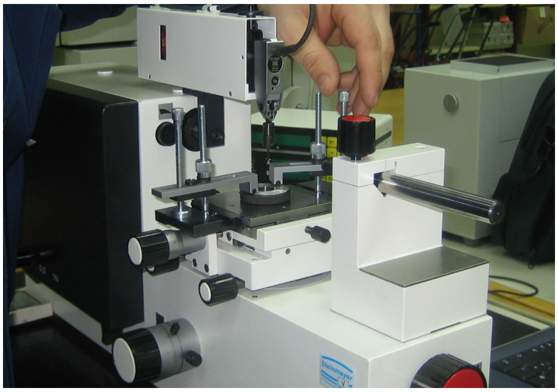

Fig. 2. *1-D measuring machine*

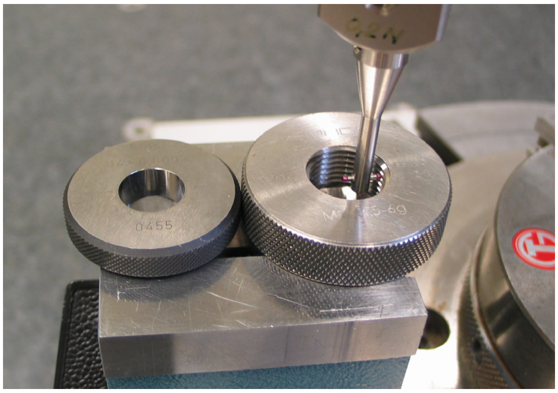

Fig. 3. *Calibration of thread ring gauge on CMM*

2 UNCERTAINTY OF PITCH DIAMETER CALIBRATION

Due to a wide range of thread ring types we decided to analyse the measurement uncertainty of metrical thread rings.

The measurement uncertainty of the pitch diameter calibration of the thread ring on a used measuring machine (which determines D_2, or which parameters of the thread ring can be determined with this machine and how accurately they can be determined, which is of even higher significance) and also depends on the number of the measured parameters of the thread ring and on the number of parameters, for which we assume to have nominal values.

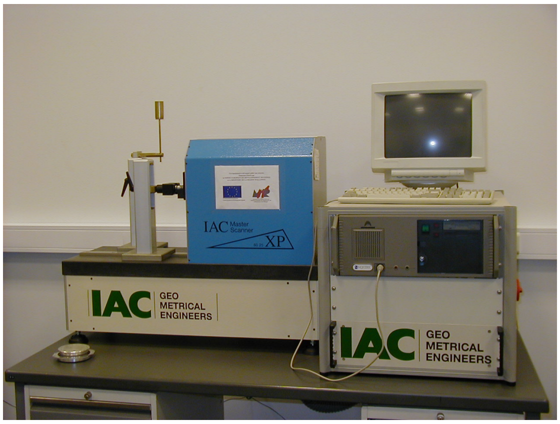

Fig. 4. *Profile scanner*

2.1 Mathematical Model of the Measurement

Bias (calibration result) is calculated by the expression according to [7]:

$$D_2 = \Delta L + C + d_D\left(\frac{1}{\sin(\alpha/2)} - 1\right) - \frac{P}{2}\cot(\alpha/2) + \frac{d_D}{2}\tan^2\psi\cdot\cos\frac{\alpha}{2}\cdot\cot\frac{\alpha}{2} - 4\cdot\sqrt[3]{\frac{1}{d_D}}\cdot a_2 + \delta B \quad (1)$$

and a_2 is short expression for

$$a_2 = \sqrt[3]{\frac{9F^2}{8}\left(\frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}\right)^2}, \quad (2)$$

where:

ΔL the average of the displacements between three positions
C stylus constant
d_D diameter of the probing element
α thread angle
P pitch
Ψ lead angle
w_0 indentation of ball-on-flat contact
ν_i Poisson-coefficient (0.28 for steel; 0.25 for ruby)
F measuring force (perpendicular to the flat)
E_i elasticity modulus ($2\cdot10^{11}$ N/m^2 for steel; $4\cdot10^{11}$ N/m^2 for ruby)
Δb accounts for imperfections of the calibrated thread gauge, such as **form deviations**, and further instrument or procedure dependent

contributions, which have not been taken into account so far.

For the contribution of thread angle uncertainty the P in the mathematical model (1) is replaced with

$$P = 2d_0 \cos\frac{\alpha}{2}, \tag{3}$$

where d_0 is the best size diameter of the probing element according to [8].

2.2 Standard Uncertainty

The standard uncertainty of pitch thread calibration is calculated [9] out of

$$u_c^2(D_2) = \sum_1^N c_i^2 u^2(x_i) + \sum_1^N \sum_1^N \left[\frac{1}{2}c_{ij}^2 + c_i^2 \cdot c_{ijj}^2\right] u^2(x_i) u^2(x_j), \tag{4}$$

where coefficients are:

$$c_i = \frac{\delta D_2}{\delta x_i},\; c_{ij} = \frac{\delta^2 D_2}{\delta x_i \delta x_j},\; c_{ijj} = \frac{\delta^3 D_2}{\delta x_i \delta x_j^2}, \tag{5}$$

and x_i are the input estimates.

For our case Eq. (4) is:

$$u^2(D_2) = u^2(\Delta L) + u^2(C) + c_{d_D}^2 u^2(d_D) + c_p^2 u^2(P) + c_{\alpha/2}^2 u^2(\frac{\alpha}{2}) + u^2(\delta B) \tag{6}$$

+ higher degree estimates.

The coefficients of first degree estimates obtained from Eq. (5) are:

$$c_{\Delta L} = \frac{\delta D_2}{\delta D_{2_{\Delta L}}};\; c_C = \frac{\delta D_2}{\delta C};\; c_{d_D} = \frac{\delta D_2}{\delta d_D}; \tag{7}$$

$$c_P = \frac{\delta D_2}{\delta P};\; c_{\alpha/2} = \frac{\delta D_2}{\delta\left(\frac{\alpha}{2}\right)};\; c_{\delta B} = \frac{\delta D_2}{\delta(\delta B)}.$$

The next step is to calculate the partial derivatives c_i, c_i and c_{ij} from Eq. (1), to obtain the sensitivity coefficients [10]. For the purpose of clarity, we shall use the tabular view. In Tables 1 and 2 the values of coefficients which were defined in Eq. (5) are shown.

The main emphasis of the research is on the influence on the uncertainty due to the theoretical angle and the thread step since the thread angle is not measured (nor the step for the first calibration) when calibrating the pitch diameter of a thread ring. Instead, the theoretical step and angle values are used.

Table 1. *The coefficients value for the first degree estimates to measurement uncertainty*

x_i	$c_i = \frac{\delta D_2}{\delta x_i}$
ΔL	1
C	1
d_D	$\frac{1}{\sin\frac{\alpha}{2}} - 1 + \frac{1}{2}\tan^2\psi \cdot \cos\frac{\alpha}{2} \cdot \cot\frac{\alpha}{2} + 6a_2\sqrt[3]{\frac{1}{d_D^4}}$
P	$-\frac{ctg\frac{\alpha}{2}}{2}$
$\alpha/2$	$\frac{2d_0\cos\frac{\alpha}{2} - d_D\cos\frac{\alpha}{2}(2+\tan^2\psi(\sin^2\frac{\alpha}{2}+1))}{2\sin^2\frac{\alpha}{2}}$
δB	1

Table 2. *The coefficients value for the second degree estimates; the • indicates that the value is 0*

x_i	$c_{ij} = \frac{\delta^2 D_2}{\delta x_i \delta x_j}$						
	x_j=	ΔL	C	d_D	P	$\alpha/2$	δB
ΔL		•	•	•	•	•	•
C		•	•	•	•	•	•
d_D		•	•	•	•	A	•
P		•	•	•	•	$\frac{1}{2\sin^2\frac{\alpha}{2}}$	•
$\alpha/2$		•	•	A	$\frac{1}{2\sin^2\frac{\alpha}{2}}$	B	•
δB		•	•	•	•	•	•

In order to determine the realistic standard uncertainty of the thread step and the thread angle, certain measurements were performed. Dental acrylic material was used in order to make casts (negatives) of some thread rings whose angles were then measured on a measuring microscope.

Table 3. *The coefficients value for the third degree estimates; the • indicates that the value is 0*

x_i	$c_{ijj} = \dfrac{\delta^3 D_2}{\delta x_i \delta x_j^2}$						
	xj_j=	ΔL	C	d_D	P	$\alpha/2$	δB
ΔL		•	•	•	•	•	•
C		•	•	•	•	•	•
d_D		•	•	•	•	C	•
P		•	•	•	•	$-\dfrac{\cos\dfrac{\alpha}{2}}{\sin^3\dfrac{\alpha}{2}}$	•
$\alpha/2$		•	•	•	•	D	•
δB		•	•	•	•	•	•

Where:

$$A = -\frac{\cos\frac{\alpha}{2}(2+\tan^2\psi(\sin^2\frac{\alpha}{2}+1))}{2\sin^2\frac{\alpha}{2}},$$

$$B = \frac{d_D(2\sin^2\frac{\alpha}{2}+\sin^4\frac{\alpha}{2}\tan^2\psi+\sin^2\frac{\alpha}{2}tg^2\psi}{2\sin^3\frac{\alpha}{2}}+$$

$$+\frac{4\cos^2\frac{\alpha}{2}+2\cos^2\frac{\alpha}{2}tg^2\psi)-4d_0\cos^2\frac{\alpha}{2}}{2\sin^3\frac{\alpha}{2}},$$

$$C = \frac{2+\tan^2\psi+2\cos^2\frac{\alpha}{2}+\tan^2\psi\cos^4\frac{\alpha}{2}}{2\sin^3\frac{\alpha}{2}},$$

$$D = \frac{2d_0\cos\frac{\alpha}{2}(2+4\cos^2\frac{\alpha}{2})}{2\sin^4\frac{\alpha}{2}}+$$

$$+\frac{d_D\cos\frac{\alpha}{2}(-\sin^2\frac{\alpha}{2}\tan^2\psi+\sin^4\frac{\alpha}{2}\tan^2\psi}{2\sin^4\frac{\alpha}{2}}-$$

$$-\frac{10\sin^2\frac{\alpha}{2}+12\cos^2\frac{\alpha}{2}+6\cos^2\frac{\alpha}{2}\tan^2\psi)}{2\sin^4\frac{\alpha}{2}}.$$

From 50 measurements of metrical thread rings, which differed in diameter and step, a standard measurement deviation was calculated. In order to confirm the assumption that in Slovenia there are a lot of thread etalons which are not at all appropriate despite their appropriate D_2 (errors from calibrations are within tolerance limits), we also performed some angle measurements on thread bolts that we received from the industry.

The angle measurements were performed by means of measuring knives on a measuring microscope. The obtained results in means of angle deviations matched the results, which have been performed on thread rings. The alternative thread angle measurement of industrial thread rings was executed on a profile scanner to calculate the pitch diameter with an adjustment technique and deviated from the measurements executed on the microscope for maximum 0.2°.

2.3 Influence of Nominal Value Parameters

When determining standard step uncertainty the data of the last thread ring step calibration was considered. The calibrations were executed on the CMM with a two-ball stylus for mechanical probing and the profile scanner to calculate the pitch diameter with an adjustment technique.

The contributions to the final measuring uncertainty of thread angle and thread pitch uncertainty (by considering nominal values instead of measured values) and the final measuring uncertainty of calibrations (determinated by research and assumed by [2]) are presented in Table 1.

3 CONCLUSION

The executed measurements performed on casts, whose deviations reached max. 2° and with a standard deviation of measurement deviations 0.5° or 30' showed that the estimation about the standard deviation anticipated in [2] was overly optimistic. It needs to be said that the thread rings, which provided the largest differences in angle measurements were all manufactured in the same manufacturing works.

Table 4. *Contributions of thread angle and thread pitch uncertainty and the final measuring uncertainty of calibrations*

			Calibration implemented on	
			1-D measuring machine	CMM machine
First degree estimates	$u(a/2)$	Assumed by [2]	1	1
		Determinated	0.29	0.43
	$u(P)$	Assumed by [2]	0	0
		Determinated	0.8	0.34
Second degree estimates	$u(d_D)\cdot u(a/2)$	Assumed by [2]	1	1
		Determinated	4.1	4.46
	$u(P)\cdot u(a/2)$	Assumed by [2]	0	0
		Determinated	4.4	3.44
Combined standard uncertainty in μm, L in m:		Assumed by [2]	1.2	1,2
		Determinated	6.4 μm + $2 \cdot 10^{-6} \cdot L$	5.9 μm + $2 \cdot 10^{-6} \cdot L$

Lower quality of thread rings would not be of great importance if mutual uncertainties and contributions from the first measuring uncertainty degree would have been considered. In addition, the guidance claims the fact that the values are independent from each other. This is true, however D_2 is calculated out of a nonlinear function and for that very reason we checked to what extent the links of the second degree influence the measuring uncertainty of the measurement.

By knowing that the values are not independent and low quality of thread rings contributes to the final measuring uncertainty, the actual angle value of the thread should not be used in the calculation of the final value D_2.

The magical boarder of measuring uncertainty for calibrating the pitch diameter of a thread ring of 3 μm is set because of very narrow tolerance limits (9 μm) in [11] for calibration of the pitch diameter of thread rings, which can be achieved with great difficulty when performing calibrations and considering the theoretical thread angle values. The introduced research leads us to re-verification of the measuring uncertainty of the mentioned procedures or at least these have to be chosen very carefully, depending on the demands of direction accuracy. According to [12] and [13] the expanded measuring uncertainty of thread ring pitch diameter calibration on the 1D-length measuring machine with a two-ball stylus for mechanical probing and CMM with a two-ball stylus for mechanical probing is greater than 10 μm, therefore these two types of calibration are suitable for calibration of industrial thread rings. Since the quality of laboratorial and adjustable thread rings is much better than that of control thread rings it is therefore possible to calibrate the later on this kind of machines, however a much greater number of measurements would be needed in order to assure a correct result or value.

Further research should be aimed at finding new principles [14] for determining the pitch diameter.

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