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ORIGINAL ARTICLE

Alignment problem while measuring thread pitch of large thread gauges on the profile-measuring machines

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Abstract The problem described in this paper arises while measuring pitch of the large-scale thread gauges with a profile-measuring machine. Analytic estimate of the thread gauge alignment uncertainty is given, which results in the accumulated error of the thread pitch measurement. The results proposed in this paper should be considered as an additional source of uncertainty while inspecting the thread pitch on profile-measuring machines.

Keywords Thread · Pitch · Profile measurement · Alignment · Uncertainty

1 Introduction

Different methods of thread pitch measurement include, but are not limited to, coordinate-measuring machines [1], profile-measuring machines [2], and special dedicated equipment (i.e., MSXL 300, developed by IAC Geometrical Engineers). The difficulties that require usage of special measuring equipment include the following:

- Large thread gauges require equipment with large X and Y measuring range.
- Mass of large thread gauges easily reach 20 kg, making usage of most standard fixtures impossible.

In this paper, limitations of one such method of thread measurement were studied. They were formerly presented in the conference proceedings [3]. The results proposed in this paper should be considered as an additional source of uncertainty while inspecting the thread pitch on profile-measuring machines. Experiments were done using M170x6 thread ring gauges on the Mahr Perthometer Concept XC20 profile-measuring machine.

2 Alignment method

This problem arises while measuring pitch on the thread gauges of large diameter and length. In our laboratory, thread pitch is measured with the profile-measuring machine as follows: a special table is placed on a machine's granite plate; the table can be rotated and shifted horizontally with micro screws as needed; the thread gauge to be measured is placed on a prism that stands on the table; the gauge is quite heavy so it does not require any additional fixtures. After this, the whole construction has to be aligned so that the measurement can be taken on the apex line of the thread. For this purpose, two extreme points on opposite sides of the gauge[1] are found with the help of a profile measurement machine to align the whole construction so that the axis of the gauge would be parallel to the line along which the Perthometer's measuring stylus travels. These points are the lowest for a thread ring gauge and the highest for a thread plug gauge. The distance between the alignment points has to be maximal and practically should be at least equal to the actual length of the thread (Fig. 1).

[1] One point on each side.

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Fig. 1 Setup overview

The alignment method described here emerges from Sub clause 5.1 of the operating instructions [4], provided by the manufacturer of the profile-measuring machines. Hence, it is clearly stated by the manufacturer

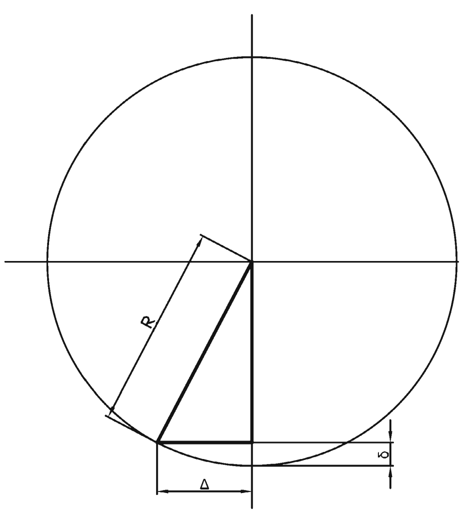

Fig. 2 Estimating alignment error (Δ)

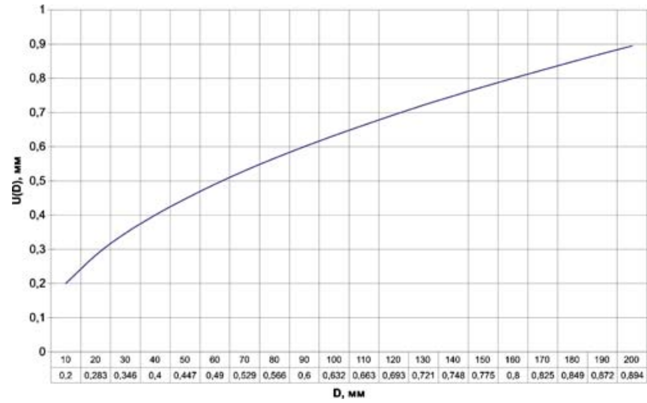

Fig. 3 Function $U(D)$ with $\delta = 0.001$ mm

that profile measuring machines can be used to measure thread parameters.

3 Uncertainty model and related works

According to the ISO Guide to the Expression of Uncertainty in Measurement [5], in most cases, a measurand Y is not measured directly, but is determined from N other quantities $X_1, X_2, \ldots X_N$ through a functional relationship: $Y = f(X_1, X_2, \ldots X_N)$.

The combined standard uncertainty of the function f can be evaluated as:

$$u(Y) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial X_i} \right)^2 \cdot u^2(X_i)}$$

The function f corresponds to the measurement process and the method of the evaluation. Depending

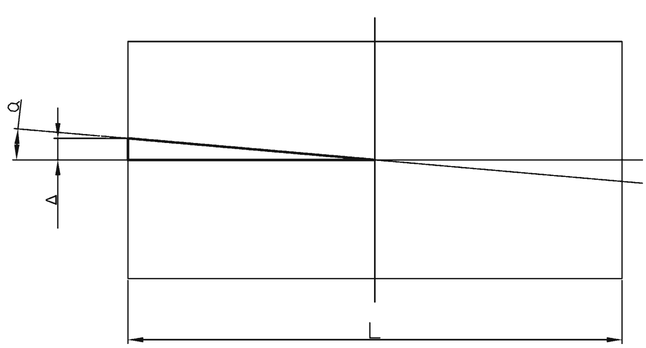

Fig. 4 Location of the measurement section

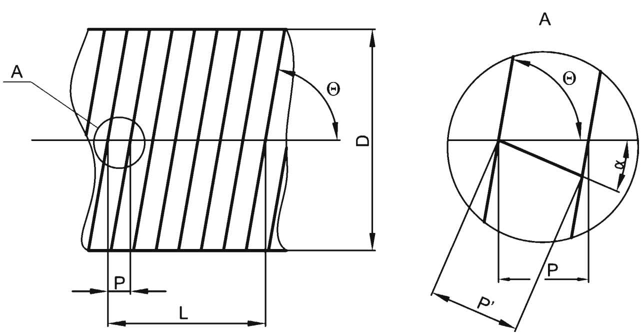

Fig. 5 Measurement section schema

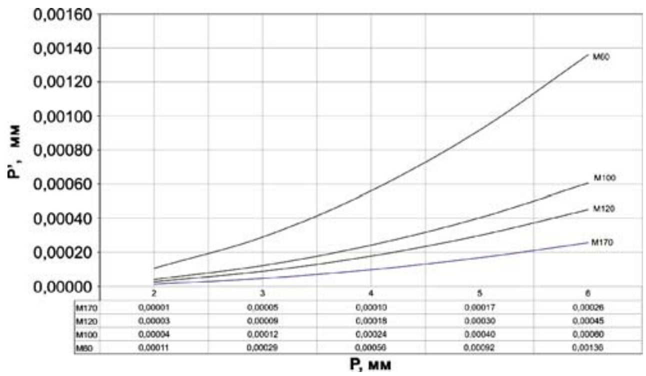

Fig. 7 Plot of $P_E(D, P, D)$

on how the standard uncertainty is evaluated, the input quantities $X_1, X_2, \ldots X_N$ may be grouped into [5]:

- Type A evaluation (of uncertainty)—method of evaluation of uncertainty by the statistical analysis of series of observations
- Type B evaluation (of uncertainty)—method of evaluation of uncertainty by means other than statistical analysis of series of observations (i.e., previous measurement data, manufacturer's specifications, handbooks)

Abiline et al. proposed [6, 7] a form measurement model for the Perthometer Concept machine, resulted in the following equation [7, Eq. 11]:

$$y = x + \delta X_{\mathrm{MI}} + \delta X_{\mathrm{r}} + \delta X_{\mathrm{F}} + \delta X_{\mathrm{CV}} + \delta X_{\mathrm{CC}} + \delta X_{\mathrm{ang}} \qquad (1)$$

The combined standard uncertainty of Eq. 1 can be determined as follows [7, Eq. 12]:

$$u(y) = \left[u^2(x) + u^2(\delta X_{\mathrm{MI}}) + u^2(\delta X_{\mathrm{r}}) + u^2(\delta X_{\mathrm{F}}) + u^2(\delta X_{\mathrm{CV}}) + u^2(\delta X_{\mathrm{CC}}) + u^2(\delta X_{\mathrm{ang}})\right]^{\frac{1}{2}},$$

where the standard uncertainties correspond to:

$u(x)$	— indication
$u(\delta X_{\mathrm{MI}})$	— measurement instrument correction
$u(\delta X_{\mathrm{r}})$	— stylus radius correction
$u(\delta X_{\mathrm{F}})$	— measurement force correction
$u(\delta X_{\mathrm{CV}})$	— surface curvature correction
$u(\delta X_{\mathrm{CC}})$	— surface concavity correction
$u(\delta X_{\mathrm{ang}})$	— surface angle correction

In this paper, a new term is introduced into Eq. 1 to model the influence of thread alignment procedure on thread pitch measurement uncertainty. This yields the pitch measurement standard uncertainty $u(\delta X_{\mathrm{pitch}})$ equal to:

$$u(\delta X_{\mathrm{pitch}}) = \frac{P_{E_L}}{\sqrt{3}}, \qquad (2)$$

where P_{E_L}—accumulated pitch error.

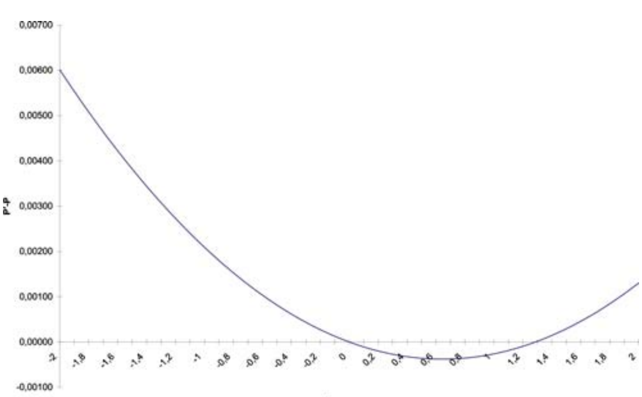

Fig. 6 Dependency of the pitch error on the rotation angle

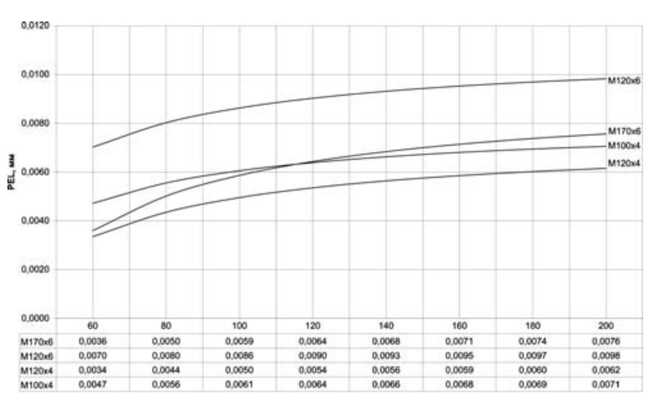

Fig. 8 Plot of $P_{E_L}(D, P, L)$

Table 1 Determination of the alignment error

Indicator, mm	8.0	8.2	8.4	8.6	8.8	9.0	9.2
Prof. Z-value, mm	0.013	0.008	0.002	−0.003	−0.006	−0.010	−0.014
Indicator, mm	9.4	9.6	9.8	10.0	10.1	10.2	10.4
Prof. Z-value, mm	−0.017	−0.019	−0.021	−0.022	−0.023	−0.023	−0.023
Indicator, mm	10.6	10.8	10.9	11.0	11.2	11.4	11.6
Prof. Z-value, mm	−0.023	−0.023	−0.023	−0.021	−0.020	−0.017	−0.015
Indicator, mm	11.8	12.0	12.2	12.4	12.6	12.8	13.0
Prof. Z-value, mm	−0.012	−0.008	−0.004	0.0	0.005	0.011	0.017

4 Alignment error

Let us construct an equation to estimate the accuracy of the described alignment method depending on the Perthometer's sensitivity.[2]

The Δ can be found using the Pythagorean theorem for the right-angled triangle (Fig. 2). The thread is symmetrical, so Δ is the half-length of the alignment error. A negligible quantity δ^2 under the radical sign can be eliminated while considering δ (device sensitivity). Then, the final equation will look the following way:

$$U = 2 \cdot \Delta = 2 \cdot \sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{D}{2} - \delta\right)^2} =$$
$$= 2 \cdot \sqrt{D \cdot \delta - \delta^2} = 2 \cdot \sqrt{D \cdot \delta}$$

The results are presented on the graphic of the function $U(D)$ (assuming[3] $\delta = 0.001$ mm) (Fig. 3).

While measuring the thread of 20 times smaller diameter, the alignment error will be reduced by 4.5 times and will be 0.2 mm.

5 Influence of the alignment error on the thread pitch measurement

While measuring thread pitch, the result is as follows: the deviations, calculated in the previous chapter, will result, in fact, in the thread measurement being performed not in the axial section of the gauge but in the section rotated to the gauge's axis by some angle. Let us determine this angle from Fig. 4.

After using the trigonometric ratios:[4]

$$\alpha = \arctan \frac{\Delta}{\left(\frac{L}{2}\right)} = \arctan \frac{2 \cdot \Delta}{L} = \arctan \frac{U}{L} \tag{3}$$

where L — length of the thread,[5] millimeters
Δ — alignment error, millimeters
α — rotation angle of the section, degrees

Putting together this equation and U from the previous section yields:

$$\alpha = \arctan \frac{U}{L} = \arctan \frac{2 \cdot \sqrt{D \cdot \delta}}{L}$$

For metric thread of M170, the value for the α angle is (assuming $L = D$):

$$\alpha_{M170} = \arctan \frac{2 \cdot \sqrt{170 \cdot 0.001}}{170} \approx 0.278°$$

From schema[6] on Fig. 5, parameters Θ and P' can be evaluated.

The Θ parameter is equal to:

$$\Theta = \arctan \frac{\pi \cdot D}{P}$$

where P—nominal pitch of the thread, millimeters.

For the thread M170x6, it is evaluated into $\Theta = \arctan \frac{\pi \cdot 170}{6} = 89.356°$

Using the sines theorem, the value of P' can be found—that is, the pitch of the thread in the section rotated to the thread axis by the angle α:

$$P' = P \cdot \frac{\sin \Theta}{\sin(\alpha + \Theta)} \tag{4}$$

The angle α could be positive or negative. Positive values represent CW rotation. In Fig. 6, there is a dependency of $P' - P$ on the α for the M170x6 thread.

The accumulated pitch error on the complete length of the thread is:

$$P_{E_L} = \frac{L}{P} \cdot P_E = \frac{L}{P} \cdot (P' - P)$$

The plot of the dependencies $P_E(D, P, L)$ and $P_{E_L}(D, P, L)$ can be drawn for different threads assuming $\delta = 0.001$ mm. First, let us consider how $P_E(D,$

[2]Here and onward, "sensitivity" stands for "uncertainty of coordinate measurement in Z direction with confidence level of 95%."

[3]According to the calibration certificate of our Perthometer Concept machine.

[4]Here and onward, we assume the distance between the alignment sections to be equal to the actual length of the thread since, for the best alignment, it is desirable to use the maximal available length of the thread.

[5]Distance between two sections for alignment. See footnote 4.

[6]Only horizontal-angle component is considered in this paper. Vertical-angle component is automatically compensated by the MarSurf XC20 measurement software (align profile feature) supplied with the Perthometer Concept and is beyond the scope of this paper.

Table 2 Influence of rotation angle on accumulated pitch error

Δ, mm	α, degrees	P_{E_L}, mm	$P' - P$, mm
−2.5	−1.461	180.081	0.00248
−2.0	−1.169	180.046	0.00141
−1.5	−0.877	180.026	0.00080
−1.0	−0.585	180.006	0.00018
−0.8	−0.468	180.000	0.0
−0.6	−0.351	179.997	−0.00009
−0.4	−0.234	179.991	−0.00028
−0.2	−0.117	179.988	−0.00037
0.0	0.0	179.985	−0.00046
0.2	0.117	179.983	−0.00052
0.4	0.234	179.982	−0.00055
0.6	0.351	179.981	−0.00058
0.8	0.468	179.982	−0.00055
1.0	0.585	179.983	−0.00052

P, L) depends on the nominal thread pitch while keeping L and D constant (also assume that $L = D$) Fig. 7. From the plot, it is clear that the pitch error increases faster for gauges of small diameter.

The influence of the measured thread length on the pitch error can be estimated (Fig. 8). The accumulated pitch error can be high, i.e., for M170x6 thread with a length of 200 mm, it is 0.008 mm. This fact should be taken into consideration during the high precision measurements of the threads. That is, the accumulated pitch tolerance zone for thread master gauges with the metric thread M170x6-6g should be within 0.006 mm. This requirement renders the usage of profile-measuring machines impossible for these threads.

6 Experimental data

Experimental data were collected on the Mahr Perthometer Concept XC20 profile-measuring machine[7] During the measuring process, the temperature was within (20 ± 0.2)°C. Deviations of temperature from 20°C were not taken into account due to their irrelevance.[8]

To be able to determine the value of U experimentally, the dial indicator[9] has to be installed to measure the movements of the table in the direction orthogonal to the Mahr Perthometer's measurement line. We put the master thread plug gauge with the thread M170x6-6g on the table and performed the alignment procedure on the length of 196 mm. We turn the micro screw to rotate the table step by step after this. Each time, the dial indicator shows the difference of 0.2 mm. We put down the results both from the indicator and Z value of the profile from the Perthometer. The results can be seen in the Table 1.

The insensible zone between 10.1 and 10.9 mm is clearly seen from the aforementioned results. That means that the accuracy of alignment cannot be better than $U = 10.9 - 10.1 = 0.8$ mm. This is very consistent with our theoretical value for this thread (0.825 mm). The dependency $P'(\alpha) - P$ shown in Fig. 6 has to be experimentally determined to check the conjecture about how the alignment error affects the accumulated pitch error. The thread gauge was placed on the Perthometer's table so that the axis of this thread gauge had some angle to the device's measurement line (angle α). The table was rotated with the micro screw and the accumulated pitch on 30 gaps of the thread was measured (that is, $30 \cdot 6 = 180$ mm) for each rotation step. Numerical value of the rotation was measured by the dial indicator.[10] Actually, the dial indicator displays the Δ value, and the Perthometer displays the P_{E_L} value. These results were collected into Table 2.

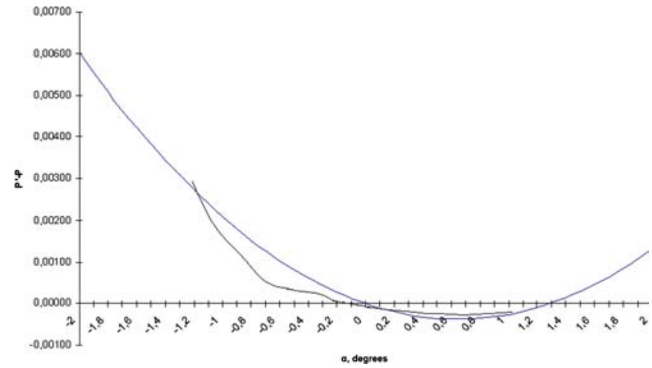

Fig. 9 Dependence of pitch error on the rotation angle

The values of α and $P' - P$ should be compared with theoretical values from Fig. 6. However, during this experiment, it was initially impossible to align the work piece perfectly (because of a non-zero U value).

To compare the results of the experiments and theoretical values, the experimental values of α have to be shifted so that a well-defined experimental extreme point (at $\alpha = 0.351$) will impose with the theoretical extreme point (at $\alpha = 0.65$). The linear value of this shift is equal to $S = 180 \cdot tan(0.65 - 0.351) = 0.94$ mm, and it is comparable to the U value for this thread

[7]$\text{MPE}_E = 2 + \frac{L}{50}$ µm with 95% confidence level.

[8]For thread with length 200 mm, the temperature error will be: $\left(0.2\,\text{m} + 0.2°\text{C} \cdot 11.0 \cdot 10^{-6}\right) < 0.5\,\mu\text{m}$.

[9]Uncertainty of 0.001 mm per 1 mm with 95% confidence level.

[10]The indicator shows this rotation as the linear displacement of the point on the edge of our thread gauge perpendicular to the measurement axis.

Table 3 Experiment results

Pitch reading, mm	Mean, mm	Std. uncertainty, mm
179.989		
179.985		
179.984		
179.987		
179.984	179.985	0.003
179.980		
179.982		
179.989		
179.984		
179.981		

(0.825 mm). Both theoretical and experimental plots are combined in Fig. 9.

One more experiment was performed. The pitch on the 30 gaps of the M170x6-6g thread was measured ten times (realigning the part after each measurement), with the results as presented in Table 3.

The theoretical value for this thread is:

$$P_{E_L} = \frac{180}{6} \cdot \left[P'(6, 170, 196) - 6\right] = 0.0069\,mm.$$

The standard uncertainty of pitch measurement for M170x6 metric thread from Eq. 2:

$$u(\delta X_{\text{pitch}}) = \frac{P_{E_L}}{\sqrt{3}} = \frac{0.0069}{\sqrt{3}} \approx 0.004\,mm.$$

The experimental result is within the theoretically evaluated value.

7 Conclusions

The results proposed in this paper should be considered as an additional source of the measuring uncertainty while inspecting the thread pitch of large-diameter threads on profile-measuring machines. The standard uncertainty can go up to 0.004 mm for M170x6 thread with a length of 200 mm. Other research activities concerning Perthometer Concept profile-measuring machines are presented in [6] and [7].

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