Task Specific Uncertainty Estimation for Roundness Measurement

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Abstract
As it is necessary to supply uncertainty with measurement [1], fast, task-specific estimation of uncertainty is needed. A concept, already successfully implemented in roughness measurement [4,5], is now adapted to be used for roundness measurements. The concept is implemented in software. As a result, uncertainty budgets for four different specimens, three ring gauges and a spherical standard, are given as examples of the presented concept. The results of these measurements show that noise and spindle errors are specimen dependent.

Calculation of uncertainty

Hybrid method
A classical on-line uncertainty budget is set up, but elements of this budget, such as spindle errors and noise effects, are estimated using Monte-Carlo techniques [3]. The uncertainty budget is given for a single measurement; for calibration of a roundness standard, averaging reversal techniques are used for which the uncertainty is much smaller. The method means that for each influencing factor virtual measurements are calculated with respect to the standard deviation of the influencing factor, related to its nominal value. For each influencing factor, the difference in parameters between the original and the virtual measurements gives the standard uncertainty per parameter per influence. If a recalculated measurement with ‘zero’ influence is used to calculate the standard uncertainty, the calculated virtual profile with nominal value for that influence is used as the nominal parameter. This way, algorithm errors are kept to a minimum. If both sides cannot be calculated, e.g. the profile recalculated with smaller radius has no additional information, only one side is used to calculate the uncertainty.

Total uncertainty
As stated by the GUM [2], the total standard uncertainty $u_m$ of measurement result $M$ can be calculated as the squared sum of the independent individual uncertainties multiplied by their sensitivity. This can be rewritten, as shown in formula 1, to express the calculation of the standard uncertainty for a selected influence $m_i$ by variation of that influence and keeping other influences nominal.

$$u_M^2 = \sum_i \left( \frac{\partial M}{\partial m_i} \right)^2 u_{m_i}^2 = \sum (M(m_1,\ldots,m_i + u_{m_i},\ldots m_n) - M(m_i))^2 \quad [1]$$

The method is a different approach to uncertainty calculation as a full Monte-Carlo calculation [3]. Here, a complete overview of influences and their uncertainty is given. The on-line calculation is carried out fully automatically and takes no extra time or effort.
Implementation
Software has been written to calculate the on-line uncertainty budget after processing a measurement. The following influences have been incorporated:

Calibration and linearity deviations of the probe
Linearity can be calibrated with a step standard, with the roundness tester on horizontal straightness mode, or a flick standard can be used. The linearity directly influences the roundness profile. The effect is simply estimated by multiplying the profile with a factor, e.g. 1.01 for a 1% uncertainty, and recalculate the parameters.

Radius probe
The radius can be measured with a measuring microscope, with a razorblade or micrometer. If the sample contains large peaks or valleys, which significantly affect the amplitude parameters, the influence of the radius is noticeable. The influence is taken as the calculated difference to a 1 mm probe radius, or any other radius the user specifies.

Contact angle probe
The relative angle between the probe and sample is almost zero at calibration. If a complex form is measured, the angle can vary from 1° up to 15°. This causes a second order non-linear effect on the measured roundness profile.

Low pass filter
Apart from the software implementation, dynamic probe characteristics may cause the real filter characteristics to deviate from the Gaussian filter. The filter characteristics can be obtained by filtering a known multi-wave specimen [6], or by dynamic probe calibration [7].

High Pass Filter
Although only used in very special cases, the implementation of the high pass filter is realized to complete the budget. The characteristics can be obtained in the same manner as the low pass filter. If used, the influence is specimen dependent.

Measurement force
Calibrated with a balance, the force can vary between 30 mN to 90 mN. The effect is estimated by correcting the profile to zero measurement force using the Hertzian deformation theory. The contribution to the total uncertainty is in the order of nanometres.

Spindle errors
The repeatable spindle error diagram is obtained with the reversal technique or multistep method of a roundness standard where the average of many measurements is taken. Once calculated, its effect on the uncertainty is estimated by adding or subtracting the spindle error to the profile, where the spindle profile is rotated in 10° steps, and calculating the standard deviation of the calculated parameter relative to the nominal.

Noise errors
As the spindle deviations are known from the reversal technique or multistep method, a typical noise profile is estimated by subtracting the average of many measurements from a single measurement of the same used specimen. The influence on the uncertainty budget is estimated in the same Monte-Carlo like way as the spindle error.

Results

Measurements have been performed on a Mitutoyo Ra 2000 Roundness tester.

Three ring gauges with different diameters are measured with a magnification of 50 000. The Mitutoyo standard is measured with a magnification of 100 000. The rotational speed is 2 revolutions per minute. All measurements are processed using L.S. reference circle and filtered at 150 UPR with the Gaussian filter. The spindle (figure 1) and noise (figure 2) diagram were obtained with reversal technique of a Mitutoyo standard. In the spindle diagram, the step of 10 nm at 0° is due to drift in the probe. In the noise diagram, the non-reproducible periodic deviation of 7 Hz is due to building vibrations. The known systematic spindle error should be corrected as advised by GUM [2], but is taken into account to illustrate the possibility to separate the error contributors.

The results are shown in table 1.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Mitutoyo Standard</th>
<th>Tesa Ring Gauge</th>
<th>Tesa Ring Gauge</th>
<th>Ring Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 mm</td>
<td>110 mm</td>
<td>50 mm</td>
<td>17 mm</td>
</tr>
<tr>
<td>Nominal Unc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncertainty RONt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RONt = 39 nm</td>
<td>RONt = 393 nm</td>
<td>RONt = 109 nm</td>
<td>RONt = 253 nm</td>
<td></td>
</tr>
<tr>
<td>Linearity</td>
<td>1%</td>
<td>4 nm</td>
<td>1 nm</td>
<td>3 nm</td>
</tr>
<tr>
<td>Radius 0.85 mm</td>
<td>10%</td>
<td>0</td>
<td>0</td>
<td>7 nm</td>
</tr>
<tr>
<td>Angle 0°</td>
<td>1°</td>
<td>0</td>
<td>0</td>
<td>0 nm</td>
</tr>
<tr>
<td>Pitch 0.05°</td>
<td>100%</td>
<td>0</td>
<td>0</td>
<td>2 nm</td>
</tr>
<tr>
<td>Force 10 mN</td>
<td>10%</td>
<td>2 nm</td>
<td>1 nm</td>
<td>3 nm</td>
</tr>
<tr>
<td>Spindle 1</td>
<td>100%</td>
<td>9 nm</td>
<td>9 nm</td>
<td>6 nm</td>
</tr>
<tr>
<td>Noise 1</td>
<td>100%</td>
<td>18 nm</td>
<td>8 nm</td>
<td>10 nm</td>
</tr>
<tr>
<td>Total (1s)</td>
<td>20 nm</td>
<td>13 nm</td>
<td>12 nm</td>
<td>14 nm</td>
</tr>
</tbody>
</table>

Table 1: Example of uncertainty budget for RONt of four specimens.

The results for these samples can be expressed in two standard deviations:

Mitutoyo Standard, RONt = 39 ± 40 nm
Tesa Ring Gauge 110 mm, RONt = 393 ± 26 nm
Tesa Ring Gauge 50 mm, RONt = 109 ± 24 nm
Ring Gauge 17 mm, RONt = 253 ± 28 nm

The results show that the spindle and noise contributions can be quite different for different specimens. For small roundness deviations the spindle and noise influences are dominant, for larger deviations the probe calibration contributes relatively more to the uncertainty.
Conclusion

A new approach to calculate the roundness measurement uncertainty is presented. With this method it is not only possible to calculate a task specific uncertainty budget (specific specimen and specific roundness tester), but the method can also be used to improve measurement results as the budget enables quantification of the major contributor to the measurement uncertainty.

Acknowledgement

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References