Use of some statistical techniques in optical metrology

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Determining accuracy of turntable by means of a theodolite and a collimator, introducing a correction curve.
REPORT
ON
THE SECOND PRACTICAL PERIOD

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INTRODUCTION

Metrology laboratory in EINDHOVEN TECHNICAL UNIVERSITY where I studied during my second practical period, is one of the practice laboratories for the mechanical engineering students. There are many kind of measurement appliances for various kind of purposes.

I especially interested in the optical ones. Therefore I made a complete experiment with the auto-collimator and theodolite using a machine tool turn table to determine its accuracy.

This experiment has been being used in practice too. Before explaining the experiment which I have done, I should like to give some information about auto-collimators only.

AUTO-COLLIMATOR

This apparatus is used for checking the alignment or straightness of nominally flat surfaces and, by an extension of the method the areas of large flat surfaces. Normally, the instrument is used for measuring the straightness of long and relatively narrow surfaces such as the beds of long lathes and planing machines. It should here be pointed out that the auto-collimator is used as a parallel beams of light source for this experiment which I have done.

The principle of the instrument is illustrated in "App: 1; Fig: 3". Referring to that figure, graticule G is situated in the principal focal plane of objective O, and is illuminated by light from the lamp S reflected by the
thin plate of clear glass \( R \). Light rays from the centre \( K \) of the graticule, lying on the axis of lens \( O \), leave the objective in a beam parallel to this axis. If this beam is intercepted by a mirror \( M \) whose reflecting surface is square to the telescope axis, then the light rays are reflected back upon their original paths, and re-entering the telescope form an image of \( K \) coincident with the point \( K \) itself. A proportion of this reflected light is transmitted by the plate \( R \) and enters the eye of the observer, who sees one image only of the point \( K \). If the mirror is inclined at an angle \( \omega \) to the axis, however, the incident light rays are reflected back at an angle \( 2\omega \) with their original direction, an re-entering the telescope they form an image of \( K \) at \( K' \), where \( KK' = f_0 \cdot \tan 2\omega \) (Fig. 3 - b). The observer then sees an image of \( K \) by light reflected back by the components of telescope, and an image at \( K' \) formed by the light reflected by the mirror \( M \). By tilting the mirror until \( K' \) coincides with \( K \), it is set accurately square to the telescope axis. Conversely, if the mirror is known to be square to this axis, then the point \( K \) can be set upon the axis by adjusting the graticule until \( K \) and its reflected image coincide. Moreover, provided that the mirror is flat, for \( K' \) and \( K \) to be sharply focused in the same plane they must both be in principal focal plane of the objective; this provides a ready means of adjusting the telescope for infinity focus, that is of setting the graticule in the focal plane.

By the provision of a suitable scale on the graticule the actual tilt of the mirror can be measured; since the reflected ray is inclined to its original direction by an angle equal to twice that through which the mirror is tilted, the sensitivity of angle measurement is twice that obtained using a telescope
and collimator of the same optical performance. Since for a tilt \( W \) of the mirror the lateral deflection in the focal plane of the objective is \( f_0 \cdot \tan 2W \), this corresponds to 0.006 in. per minute for an object glass of 10 in. focal length.

Any problem in which the tilt of a carriage is to be observed, such as in the examination of a machine bed or surface plate for straightness, can be dealt with using an autocollimator by securely mounting a mirror on the carriage. As in the case of telescope and collimator, the accuracy of such measurements is independent of the distance between instrument and mirror, provided that atmospheric conditions do not impair visibility. For a given range of measurement, however, the maximum operative distance is limited, this limitation being set by the maximum angle it is required to measure and the diameter of the objective. For tilt to be measurable the reflected light rays must re-enter the objective, and it is apparent that the farther away the mirror is from the object glass the smaller is the permissible tilt for this condition to be satisfied.

As I have mentioned before, the autocollimator is used only for auxiliary purpose in my experiment. That is to say it was only a fix target for the theodolite measurement. (See app:1, Fig:2)

EXPERIMENT

A - Problem:

To estimate the setting error of the turn-table and introduce a correcting curve.

B - Setting: (See: Fig: 1)

Theodolite is set in the center of the turn-table. The scale of the
theodolite is in g o n. (400 gons = 360 degrees of arc.)

Every 6 revolutions of the handwheel corresponds to 20 gons = 1.8 degrees of the turn table.

I have taken the theodolite readings for each 20 gons in two revolution of the turn-table. Results are tabulated in (app:2). In every setting of the table two readings are made just changing the theodolite setting.

C - Solution

- Measuring error of the turn-table is 7,71 second of arc for each setting of the handwheel.

- Correction curve is drawn in (app: 4).

D - Motivation

Through the columns nr:4 and 8:

R = 0.6611 gons is calculated. Apart from that value:

\[ S_t = f.R = 0.887 + 0.0011 = 0,00098 \text{ gons} = 3,18 \text{ second of arc}. \]

This is the theodolite reading error.

(App: 3) has been showing the range chart of reading angles. Where:

\[ \text{U.C.L.} = 2.81 + 0.0011 = 0.0031 \text{ gons.} \]

\[ \text{L.C.L.} = 0.04 + 0.0011 = 0.00044 \sim 0 \text{ gon.} \]

Since all the values are within the statistical control limits, there is no systematic difference between the range values.

The column nr: 10 is showing the differences between 5th and 9th columns. Through this column:

\[ a = 0.00142 \text{ gons}. \]
$S_d = 0.0035 \text{ gons.}$

are calculated. Where:

$$S_d = \text{Measuring error of the whole system and composed of two errors:}$$

$$S_d = \sqrt{S_t^2 + 2 S_m^2}$$

Where: $S_t = \text{Theodolite reading error} = 0.00098 \text{ gons}$

$S_m = \text{Setting error of the turn-table}$

Thus:

$$S_m = \sqrt{\frac{S_d^2 - S_t^2}{2}} = \sqrt{\frac{0.0035^2 - 0.00098^2}{2}} = 0.00238 \text{ gons}$$

$7.71 \text{ second of arc}$

**D-Conclusion:**

This is the measuring error of the turn-table which I wanted to find out.

**NOTE:** There is no systematic difference between the values in the column nr 10. Because:

$$\text{Hyp: } \alpha = 0.05$$

$$d = 0$$

$$t = \frac{d}{S_d \sqrt{\frac{21}{2}}} = \frac{0.00142 \cdot \sqrt{21}}{0.0035} = 1.86$$

$$1.86 < t_{1-\frac{\alpha}{2}} (20) = 2.086$$

Thus, hypothesis is accepted.

**-------------------------------------**

(App: 4) is showing the cumulative correction curve through the values in column nr 12. Calculation of this column values is made as follow:
First value:

\[
\frac{100,8846 + 100,8791 - (80,8845 + 80,8773)}{2} = 20,0010
\]

\[
20,0010 - 200,0000 \text{ (nominal value)} = + 0,0010
\]

Second value:

\[
\frac{80,8845 + 80,8773 - (60,8807 + 60,8742)}{2} = 20,0035
\]

\[
20,0035 - 20,0000 = + 0,0035
\]

Cumulative: 0,0010 + 0,0035 = + 0,0045 and so on...

**Conclusion:**

Giving this curve to the operator who uses this turn-table, a corrective action can be taken just regulating the handwheel in order to eliminate the existing error.
**Fig: 1)** SET-UP

**Fig: 2)** PRINCIPAL

**Fig: 3)** AUTOCOLLIMATION
<table>
<thead>
<tr>
<th>Setting angles (degree)</th>
<th>First revolution of the turn-table</th>
<th>Second revolution of the turn-table</th>
<th>Difference between first and second revolution means (Gon)</th>
<th>Cumulative correction values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First reading (Gon)</td>
<td>Second read. (Gon)</td>
<td>Range (Gon)</td>
<td>Mean (Gon)</td>
</tr>
<tr>
<td>0</td>
<td>100.8841</td>
<td>100.8851</td>
<td>0.0010</td>
<td>100.8846</td>
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<tr>
<td>18</td>
<td>80.8841</td>
<td>80.8850</td>
<td>0.0010</td>
<td>80.8845</td>
</tr>
<tr>
<td>36</td>
<td>60.8810</td>
<td>60.8804</td>
<td>0.0006</td>
<td>60.8807</td>
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<td>54</td>
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<td>40.8796</td>
<td>0.0004</td>
<td>40.8794</td>
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<tr>
<td>72</td>
<td>20.8769</td>
<td>20.8788</td>
<td>0.0019</td>
<td>20.8779</td>
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<tr>
<td>90</td>
<td>0.8705</td>
<td>0.8712</td>
<td>0.0007</td>
<td>0.8709</td>
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<tr>
<td>108</td>
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<td>380.8638</td>
<td>0.0018</td>
<td>380.8629</td>
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<tr>
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<td>360.8647</td>
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<td>0.0011</td>
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<tr>
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<td>280.8725</td>
<td>0.0006</td>
<td>280.8722</td>
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<tr>
<td>216</td>
<td>260.8720</td>
<td>260.8729</td>
<td>0.0009</td>
<td>260.8725</td>
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<tr>
<td>234</td>
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<td>240.8711</td>
<td>0.0002</td>
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<tr>
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<tr>
<td>360</td>
<td>100.8831</td>
<td>100.8799</td>
<td>0.0032</td>
<td>100.8855</td>
</tr>
</tbody>
</table>
RANGE CHART OF READING ANGLES

(See app. nr. 2, column 4 and 8)
CORRECTION CURVE FOR TURN-TABLE SETTING

(See app. 2, column 12)