A study of key optical profiler parameters for form error measurement

X. Huang and Y. Gao

Department of Mechanical Engineering, Hong Kong University of Science and Technology
Clear Water Bay, Kowloon, Hong Kong SAR, China, E-mail: ameygao@ust.hk

Abstract

Optical profiler is a typical modern device for precision form error measurement. In our use of the equipment, we found that the surface form profile after stitching is ambiguous if the lens magnification is changed. The error in terms of PV value can be up to 3200% when the lens magnification changes from 2.5 times to 30 times. This has been confirmed by the equipment supplier. It is worthwhile to offer a comprehensive study as many users may use the instrument of the kind straightforward without detailed investigation of the performance. We found that, among the 6 key parameters studied, 3 independent parameters are more important. For the 3 independent parameters, we recommend to set the magnification \(A=2.5 \text{ times}\), the resolution \(r=0.5\), and the overlap \(p=20\%\). With the recommended settings, the measurement error can be less than 0.5\%. Backscan and length for scanning in the vertical direction, and cut off frequency for delivering form profile are less critical compared with the three independent parameters.

Keywords: Form error, stitching, optical profiler, uncertainty, magnification, overlap

1. Introduction

Size, form and roughness are the three critical features of a workpiece according to their spatial frequencies. Form error is more difficult to handle because the evaluation issues are more complex [1-2]. ISO has planned a standard system concerning the definition of terms and concepts related to form error [3]. Optical method is widely used for form error measurement because it is noncontact and nondestructive to precision workpiece surfaces. Optical profiler is a typical modern device of the kind and it is typically based on white light interferometric technique.

Stitching. To obtain the workpiece surface form error, a surface area is to be measured. Interferometric microscope yields high resolution but only over a small area. High spatial resolution over a large field of views or FOV can be obtained by stitching together multiple adjacent high spatial resolution measurement areas [4].

In a Wyko optical profiler that was used by us, we found that the surface profile after stitching is ambiguous causing an error up to 3200% if the lens magnification \(A\) is changed from \(A=2.5\) times to \(A=30\) times. Measurement uncertainty would become severe if a larger magnification \(A\) is used. The problem was confirmed by the equipment supplier. As many users who may use an instrument of the kind straightforward without detailed investigation of the performance, it will be worthwhile to offer a comprehensive study of the key parameters of the instrument of the kind, so that the problems can be easily identified and resolved. For this purpose and in this study, we studied peak to valley PV of surface profiles of two types of samples under different operational conditions of the optical profiler. One sample is mild steel and the other one is silicon. Both have acceptable surface form accuracy.

2. Key parameter study

Parameter settings. Table 1 shows the 6 key parameter settings for the mild steel and silicon samples. Magnification \(A\) equals to objective lens magnification multiplying FOV value as the objective lens magnification and FOV are combined together. It is noted that,
apart from the study of $f_c$ (Table 1), no filtering was used in the studies of the other 5 parameters (Table 1).

Table 1. Parameter settings for use of the Wyko optical profiler for mild steel and silicon samples.

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
<th>Settings</th>
<th>*</th>
<th>**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Objective</td>
<td>5x</td>
<td>10x</td>
<td>20x</td>
</tr>
<tr>
<td>Basic</td>
<td>FOV</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Resolution r</td>
<td>(Sampling interval $\Delta x$)</td>
<td>Quarter</td>
<td>Half</td>
<td>Full</td>
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<tr>
<td>Stitching</td>
<td>Overlap p (%)</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>VSI</td>
<td>Backscan $b$ ($\mu$m) **</td>
<td>39/44</td>
<td>41/46</td>
<td>43/48</td>
</tr>
<tr>
<td>Filtering</td>
<td>Length l ($\mu$m) **</td>
<td>15/31</td>
<td>17/33</td>
<td>19/35</td>
</tr>
<tr>
<td></td>
<td>Cut off frequency $f_c$ (1/mm)</td>
<td>15</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

* Bold setting values are the default values for studying other parameters.

** First value for steel and the second value for silicon.

** Effects of magnification A. PV value of form profile could change significantly when the magnification $A$ increases from $A=2.5$ times to $A=30$ times (Fig. 1(a-b)). For the mild steel sample, the maximum PV value can be 78.9$\mu$m which is approximately 32 times larger than the original value of 2.4$\mu$m. The measured form profile $y(x)$ was distorted (Fig. 1(c)). Distortion occurred again for the Wyko test sample which has a certified PV value of 10.02±0.085$\mu$m for device calibration (Fig. 1(d)). The measurement error was up to 3200% (Fig. 1(a)) if $A=15$ times (Fig. 1(a)).

** Fig. 1. Form error PV values and surface form profiles.

The technical support of the supplier Veeco confirmed the problem and identified that the early version control software of the equipment is the source of the problem. For the existing
profiler of the type, a low magnification at $A=2.5$ is recommended. The error can be less than 0.5% (Fig. 1).

**Effects of resolution $r$ and sampling interval $\Delta x$.** Lateral resolution $r$ refers to the smallest distance the optical profiler can accurately measure [5]. $r$ is the form profile sampling interval $\Delta x$. There are three options, full, half and quarter, represented by 1, 0.5 and 0.25, respectively (Fig. 2). The full option gives the smallest sampling interval. With the higher resolution, more peak or valley points will be likely sampled. As such, the $PV$ value of surface form profile increases with the resolution $r$ (Fig. 2(a-b)). If higher resolution is used, higher amount of surface form error data will have to be processed. For a large area, the amount of data may be beyond the instrument capacity. Balancing the factors, the option of half resolution is recommended.

![Graph showing PV values of surface form profiles against resolution $r$.](image)

(a) For mild steel sample.

Effects of backscan $b$. Backscan $b$ (Fig. 3) is a length for vertical scanning (Fig. 3(b)). The plane of focused height is determined (Fig. 3(b)) when interferometric fringes almost fill up the area of view. The plane actually determines the reference height for the lenses. Backscan $b$ determines a working range of lens above the reference height or the plane of focused height (Fig. 3(b)). Backscan $b$ value should be larger than the distance between the largest peak height and the reference height (Fig. 3(b)). The larger the backscan $b$, the higher possibility in obtaining the peak point of the surface form profile. $PV$ value is typically larger when $b$ increases (Fig. 3).

![Graph showing PV values of surface form profiles against backscan $b$.](image)

(a) For mild steel sample.

(b) For silicon sample.

Fig. 3. PV values of surface form profiles against backscan $b$.  

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Effect of length $l$. Length $l$ (Fig. 4) is one for vertical scanning and is the working range of lens below the plane of focused height (Fig. 4(b)). Length $l$ value should be larger than the distance between the largest valley height and the reference height (Fig. 4(b)). The larger the length $l$, the higher possibility in obtaining the valley point of the surface form profile. PV value is typically larger when $l$ increases. However, to avoid long measurement time used in scanning, $b$ and $l$ should be limited (Table 1).

**Effects of overlap $p$.** Overlap $p$ (Fig. 5) is a distance ratio $D_o/W_c$ for measurement area stitching (Fig. 5(b)). The larger the overlap $p$, the easier it is to match data sets. In this case, more data sets are needed to obtain surface of a field of view. In the meantime, errors may accumulate if more data sets are used and therefore trade off is necessary [4]. In our study, the PV value of form profile was found small and stable if $p=15-20\%$. This result is in agreement with the typical $p$ value of 20\% [4].

**Effects of filtering cut off frequency $f_c$.** Filtering cut off frequency $f_c$ is used to filter out high spatial frequency components for delivering form error profiles. Surface form and roughness is in mid and high spatial frequency range, respectively. If $f_c$ is small, more high frequency components will be removed. In this case, the form profile will be smoother and consequently PV will become smaller (Fig. 6). It is noted that in our study of other parameters (Table 1), for consistency, filtering was not used (Fig. 1-5).
3. Discussion
To identify the key parameters, variations of $PV$ affected by a particular parameter (Table 1) were studied (Table 2). The variation of $PV$ was estimated as $\Delta PV=\max(PV)-\min(PV)$ for the parameter. It can be seen that, among the 3 independent parameters (Table 2), the magnification $A$ and overlap $p$ are more important (Table 2). For the remaining 3 parameters (Table 2), no recommendations can be made as their values are more likely dependent on actual workpiece surface features. It is noted that $\Delta PV$ includes the effects of measurement noises (Table 2).

![Graph](image)

(a) For mild steel sample.
(b) For silicon sample.

Fig. 6. PV values of surface form profiles against filtering cut off frequency $f_c$.

Table 2. Results of the study for the 6 key parameters.

<table>
<thead>
<tr>
<th></th>
<th>Mag. $A$</th>
<th>Res. $r$</th>
<th>Ove. $p$ (%)</th>
<th>Bac. $b$ (μm)</th>
<th>Len. $l$ (μm)</th>
<th>$f_c$ (1/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta PV$ of mild steel (μm)</td>
<td>76.5</td>
<td>0.19</td>
<td>0.91</td>
<td>0.56</td>
<td>0.27</td>
<td>0.57</td>
</tr>
<tr>
<td>$\Delta PV$ of silicon (μm)</td>
<td>35.7</td>
<td>0.2</td>
<td>1.9</td>
<td>1.1</td>
<td>1.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Range of the parameter</td>
<td>2.5 - 30</td>
<td>0.25 - 1</td>
<td>1 - 50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suggested setting</td>
<td>2.5</td>
<td>0.5</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Conclusion
Compared with size and roughness, form error is more difficult to handle. The error of an optical profiler can be as large as 3200% and this has been confirmed by the equipment supplier. It is worthwhile to offer a comprehensive study as many users may use the instrument of the kind straightforward without detailed investigation of the performance. We found that, among the 6 key parameters studied, 3 independent parameters are more important. For the 3 independent parameters, we recommend to set the magnification $A=2.5$ times, the resolution $r=0.5$, and the overlap $p=20\%$. With the recommended settings, the measurement error can be less than 0.5%. Backscan and length for scanning in the vertical direction, and cut off frequency for delivering form profile are less critical compared with the three independent parameters.

5. Acknowledgement
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References