The assessment of residual flatness errors in focus variation areal measuring instruments

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Abstract

Optical instruments for areal surface topography measurement rely on high-precision lenses that guide the light from the object surface to the image plane. Lens aberrations may cause distortion of the transmitted image and consequently a residual flatness error in the measurement data. Previous work at NPL suggests using an averaging method for residual flatness error assessment for optical surface topography instruments. However, the averaging method does not apply to the focus variation technique, which relies on the nano-scale roughness of a surface to allow acquisition of topography data. This paper presents alternative methods for measuring residual flatness for focus variation instruments.

1 Introduction to focus variation

The development of the focus variation (FV) method can be traced to the extraction of three-dimensional data maps in high resolution electron microscopy [1]. The method involved the acquisition of many closely spaced images followed by data processing and was found to be applicable to optical systems. Large image views were demonstrated in terms of ‘depth from focus’ during the mid to late 1980s [2], where a series of images was acquired each with a different focal plane position. This concept was then further developed and termed ‘shape from focus’ (SFF) [3]. The SFF or focus variation method is now applied within commercially available surface topography measuring instruments [4].

In the relevant ISO committee (TC 213), a number of metrological characteristics have been put forward to allow the calibration of areal surface measuring instruments [5]. One of these characteristics is the flatness of the instrument reference. Geometric flatness is defined as the separating distance of two virtual parallel planes bracketing a surface, in between which all measured points are confined [5]. For any surface topography optical instrument, residual flatness is a systematic error introduced into every measurement by the optical system [5]. The ideal method to measure an optical instrument’s residual flatness is by measuring a perfect optical flat. Any measurement outside the instrument manufacturer’s flatness specification may be designated as a fault of noise or residual flatness of the instrument, recognizing that additional error terms may also be present. Instrument residual flatness term is typically dominated by low frequency components.

NPL has developed an averaging method (based on prior work by the German VDI/VDE committee) for which ten measurements of the flat are carried out to account for imperfections in the optical flat [6]. The images are numerically summed, with the resulting *Sz*, which is the maximum height of the scale limited surface, value generated by dividing the summation by the number of images. To achieve data acquisition, the FV method requires a minimum level of nano-scale roughness (typically 10 nm or more) on a surface, consequently the NPL method is not applicable to FV instruments. This paper presents two alternative methods for residual flatness measurement for FV.

2 Methods for residual flatness measurements

The method for residual flatness error assessment is designed to mitigate any minor roughness and waviness terms in each individual image.

- Ten images are randomly acquired over the reference flat surface.
- The images are levelled using a least squares fit.
- A DC threshold is applied to exclude the measurement of “volume-less” spikes.
- All processed images are numerically added together on a pixel by pixel basis.
- The *Sz* parameter of the final summed image is calculated.
- The *Sz* value is divided by the number of images producing the flatness value.

The inherent roughness of artefacts specifically designed for FV (and more significant underlying waviness terms) casts doubt on the final residual flatness values generated via a ten-image method. In this case a roughened flat artefact was used (*Ra* = 37 nm), using an Alicona InfiniteFocus G4 (PTB traceable for step height measurements and some other applications) with data processed using Taylor Hobson

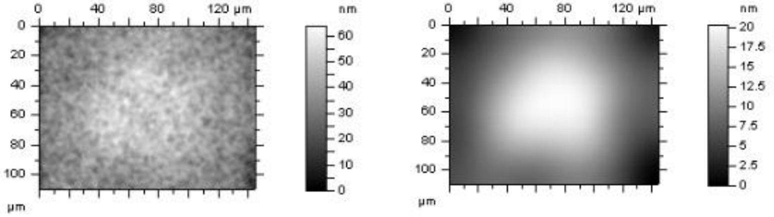
Talymap v5.1 (DigitalSurf – Mountains v5.1). Measurements were completed at 20˚C ± 0.5 ˚C.

The first alternative (more rigorous) method for obtaining the residual flatness value involves taking one hundred surface images from the roughened flat. This process then uses the same method described above but is more time intensive.

The second alternative method is to maintain the ten-image method with the roughened flat, but post process the three-dimensional result with an appropriate band pass filter to isolate the underlying signal components that contribute directly to the *Sz* residual flatness value.

3 Results and discussion

Images from the proposed alternative methods are shown in Figure 1 (100× objective lens) although the research also considered 10×, 20× and 50× objectives.



(a) (b)

Figure 1: Residual flatness images at 100×; (a) 100 images, (b) 10 images/filter

Table 1: Processed residual flatness data for each lens

Lens	*Sz* - 10 images /nm	*Sz* - 10 image/filter /nm	*Sz* - 100 images /nm
10×	204.0	4.1	7.3
20×	28.0	5.5	1.4
50×	18.6	2.6	1.0
100×	12.2	2.0	0.6

The numerical results from the experimentation are shown in Table 1. There is reasonable correlation between the 100-image method and the 10-image/filter method improving further for the higher magnification lenses. The flatness value of the 100-image results and the waviness component are comparable. This suggests that the more rigorous approach used with the 100-image method may be producing a more reliable assessment of FV residual flatness, supported by evidence from the filtered 10-image data sets, although these are typically higher in value.

In comparison, the 10-image method (used for other optical instruments) reports significantly higher residual flatness values, suggesting that it incorrectly evaluates the FV method residual flatness errors. This leads to the following conclusions.

- The NPL 10-image method for residual flatness evaluation may significantly over-estimate error values for FV instruments.
- A 100-image method generates more realistic residual flatness error values for FV instruments.
- Further processing (filtering) of 10-image method results, produces error terms that are in agreement with the 100-image method.
- Low magnification lenses may be more prone to potential form errors in rough artefacts, thereby producing overlarge estimates of instrument residual flatness.

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