Fast and information-efficient microdeflectometry with travelling cross-fringes

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Microdeflectometry (µPMD) measures the height of microscopic smooth objects with a precision in the nm-regime. Its depth scanning is slow, as at least six exposures at each depth position are necessary, which does not allow for a continuous scan. We demonstrate a novel approach with a "travelling" cross-fringe pattern to improve the scanning speed significantly.

1 Background

The inspection of specular surfaces at microscopic scale (e.g. wafers, solar-cells, biological objects) is an important task in industry and research. There are established methods such as laser scanning, confocal microscopy and white light interferometry. Here we will report an alternative method – microdeflectometry (µPMD) [1] with novel features.

µPMD is a microscopic modification of phase measuring deflectometry [2]. It measures the local slope with lateral resolution better than 1 µm and slope resolution in the range of 1 mrad. By numerical integration of the slope data, the height map can be calculated. Compared to other methods, it displays a unique feature: an extremely high sensitivity against local depth variations, dependent only on the SNR.

Exploiting µPMD to measure objects with large height dynamics, we need to overcome the small depth of focus (DOF) of the microscope objective. To extend it, we scan the object to multiple depth positions along the z-axis and determine all surface points in focus for each position. To collect this information, we combine microdeflectometry with structured illumination microscopy (SIM) [3,4].

2 Problem

In the laboratory, this method delivers a robust and highly precise height map on specular surfaces. However, for industrial application it lacks speed, as the axial scan can not be performed continuously due to the phase-shifting mechanism for measurement of contrast and phase at each z-position.

This problem has been partially solved with a "travelling" pattern introduced in [5], for one orientation of the projected grid. During a continuous depth scan, it is shifted on-the-fly. We project the phase $0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}, \ldots$ while the translation stage positions the object at $z_1, z_2, z_3, z_4, \ldots$. An intensity correlogram is measured in each pixel. Contrast and phase are evaluated by single-sideband (SSB) demodulation. Exploiting this approach, the number of required exposures per z-step could be reduced from 4 to only 1 exposure, avoiding stop-and-go scanning, and enabling a considerably faster measurement.

Deflectometry, however, requires two pattern orientations (for both components of the surface gradient), which makes it slow and we are again trapped by the "stop-and-go" limitation. To get rid of this problem, we ask: Can those two patterns be combined into one single grid to achieve a continuous scan?

3 Solution: Travelling cross-fringe

The answer is illustrated in Fig. 1. We incorporate the two grids into one single cross-fringe sequence and as before, we shift the pattern, project the next image and move the object to the next z-position at the same time.

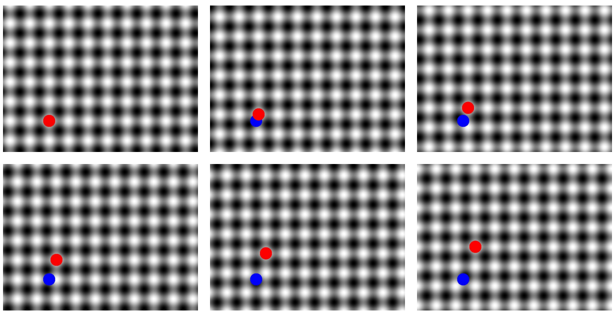

Fig. 1 *Sequentially projected cross-fringe patterns. Vertical pattern is phase-shifted* $\frac{2\pi}{8}$*, horizontal pattern* $\frac{2\pi}{3}$

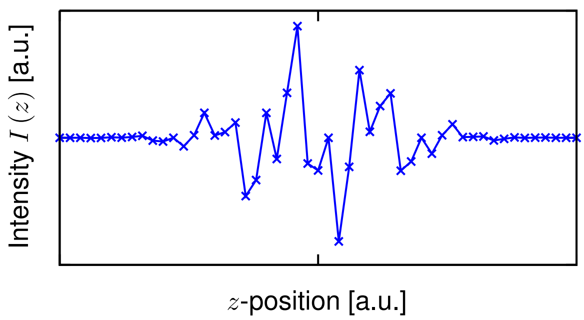

Fig. 2 *Measured intensity signal of the cross-fringe pattern (c.f. Fig. 1) in one camera pixel*

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Projecting the cross-fringe, we apply a $\frac{2\pi}{8}$-shift on the vertical pattern contribution and a $\frac{2\pi}{3}$-shift on the horizontal pattern contribution. The measured intensity signal is shown in Fig. 2.

The pattern looks somewhat obscure, but we can decipher it by the same analysis as described above. Since we chose a different phase-shifting for the x and y orientated patterns, their carrier frequencies differ. Accordingly, both signals are now distinguishable in the Fourier domain (see Fig. 3).

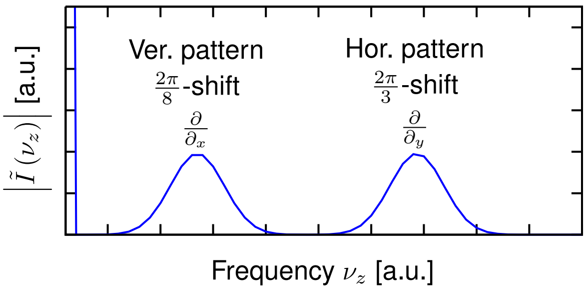

Fig. 3 *Fourier transformed intensity signal (of Fig. 2) with both components of the gradient* $\left(\frac{\partial}{\partial_x}, \frac{\partial}{\partial_y}\right)$ *distinguishable*

The next steps are straightforward. We isolate one signal component via SSB filtering, retransform it and calculate the phase. Then we apply the same procedure for the second component of the gradient. The travelling cross-fringe procedure enables to measure the full slope of the surface by just one single image per z-step and a continuous depth scan.

4 Examples

To verify this approach, we measure the slope of a mirror, tilted by 15° (Fig. 4).

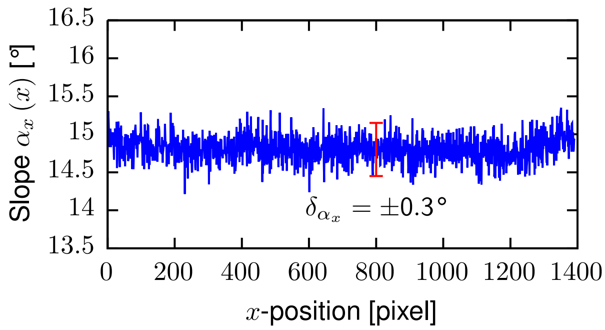

Fig. 4 *Measured slope of a 15° tilted mirror (x-profile)*

Finally, we demonstrate the cross-fringe method by a more complex object, the compound eye of a dragonfly. We first measure the slope data and then integrate it to obtain the height map that is shown in Fig. 5.

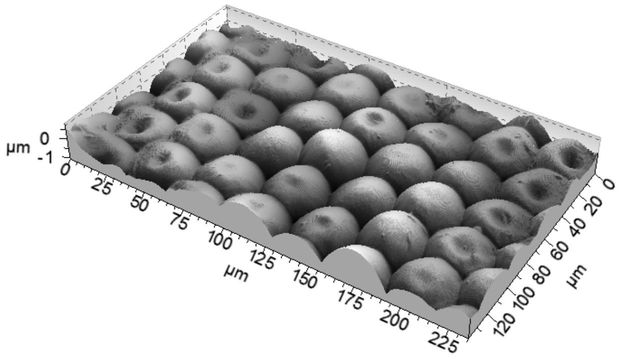

Fig. 5 *Height map of the compound eye of a dragonfly (The holes in the center of the micro-lenses are no artefacts, they are caused by drying of the object)*

5 Conclusions

We demonstrate that fast and information-efficient microdeflectometry is possible, exploiting travelling cross-fringes. We achieve a precision comparable to the classical method, while we reduce the measurement time significantly. There is a further great advantage: the approach simplifies the experimental set-up as it requires only one static chrome-on-glass pattern. No electronically controllable display is required.

References

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