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Paper Summary

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Sub-Nanometer Resolution for the Inspection of Reflective Surfaces Using White Light

Werner Juptner, Thorsten Bothe 2009 SPIE

Most optical surfaces today are measured using interferometry. A wavefront of a desired shape/curvature is reflected on the surface and recombined with another wavefront. The deviations and errors in the surface show up as fringes giving the user sub-wavelength measurements. This works well for rotationally symmetric surfaces but as optical designs and manufacturing processes are progressing there is a pressing need to measure more complicated surfaces. Freeform surfaces are revolutionizing the world of optics with the diamond turning process becoming cheaper faster and more accurate, but measuring such a surface has proven to be difficult. It is hard to create a wavefront to match the freeform shape quickly and accurately making interferometry not very effective. Some methods involve using diffractive elements to generate the complex wavefront, but this is expensive and requires a new piece to be manufactured for each surface to be tested [2].

Juptner and Bothe have presented in their paper a method capable of measuring specular reflective surfaces with sub-nanometer accuracy. The system is very simple using a camera and LCD screen. The LCD screen displays sinusoidal fringes and the camera looks at the reflection of the image off of the specular surface. The setup is shown below in Figure 1.

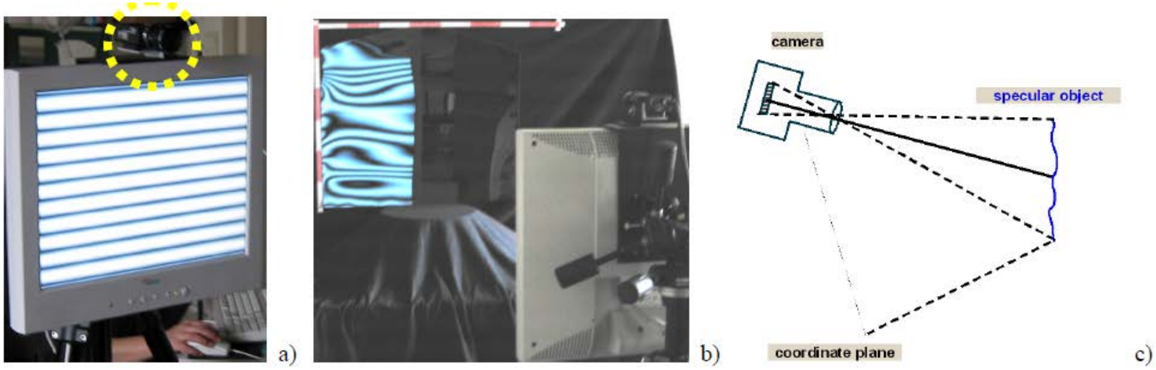

Fig. 1. System components: a) monitor displaying the fringe system and a CCD camera fixed on top of the monitor (dash line circle), b) car window (test object) at the left and monitor from back side at the right, c) schematic sketch

Any surface shape variations will cause a distortion in the reflected fringe pattern as seen in Figure 1.b. After an image has been captured, the process is repeated with a shifted fringe pattern. 4 fringe patterns each shifted by a ¼ phase allows us to use the phase shifting algorithm developed by James Wyant [3].

$$I(x,y) = I_{dc} + I_{ac}\cos[\underset{\text{measured object phase}}{\phi(x,y)} + \overset{\text{phase shift}}{\phi(t)}]$$

$I_1(x,y) = I_{dc} + I_{ac}\cos[\phi(x,y)]$	$\phi(t) = 0$ (0°)
$I_2(x,y) = I_{dc} - I_{ac}\sin[\phi(x,y)]$	$= \pi/2$ (90°)
$I_3(x,y) = I_{dc} - I_{ac}\cos[\phi(x,y)]$	$= \pi$ (180°)
$I_4(x,y) = I_{dc} + I_{ac}\sin[\phi(x,y)]$	$= 3\pi/2$ (270°)

$$\boxed{\mathrm{Tan}[\phi(x,y)] = \frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}}$$

Fig. 2 Shows the how four phase shifted fringe patterns can determine the slope at any point in the image

Using the equation above we can determine the slope at every point in the field of view of the camera. We can then integrate the slope across the surface to determine the shape profile. The resolution of the system is defined by the following equation.

$$\Delta z = pixel \frac{1}{2k} \frac{\Delta\varphi}{2\pi}$$

Pixel is the camera pixel size typically around 10µm. *k* is the f/# of the camera which is limited to around 16 to reduce the amount of noise. Δφ is detectable phase change which is usually around 1/100. This comes out to a Δz of 6.3nm. Juptner and Bothe claim to be able to reduce the Δφ by a factor of ten and reducing the overall system resolution to 0.63nm.

The method for achieving such a high phase resolution is hierarchical phase shifting. By replacing the typical amount of fringes with a higher frequency fringe pattern you can find an optimal fringe period that minimizing the effect of the noise. This method is described in more detail by Osten [3].

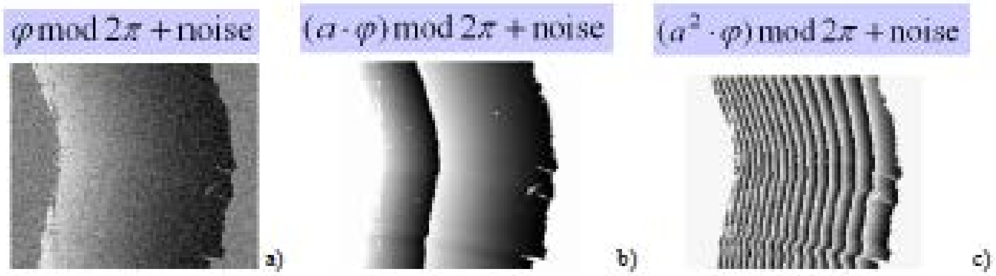

Fig. 4. Sequential fringes system a) fundamental spatial frequency b) a time larger spatial frequency than a), c) a*a larger spatial frequency that a)

The first test described in this paper was a coated mirror with a slight cylindrical shape. The shape measurement was first done using a Zygo phase shifting interferometer to be used for shape verification. Then the piece was tested using the fringe projection technique. The resulting surface profiles are shown below in figure 3.

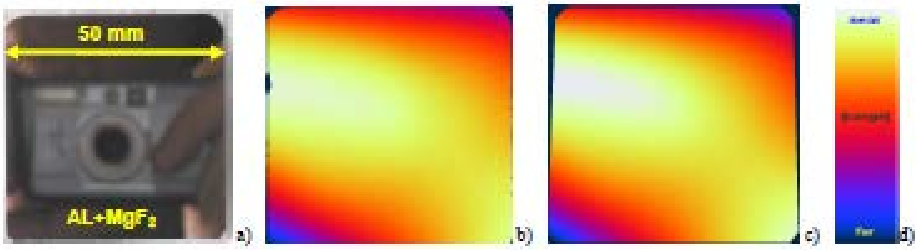

Fig. 5. Flat Al-mirror coated a) photo, shape measured b) by grating interferometer with range 21.4µm c) by fringe reflection technique 18.8µm d) color scale

Both test showed a peak-to-valley error of approximately 20µm. The cynlindrical surface shape could then be subtracted out and the fine structures of the surface could be examined. The physical limitations of the interferometry method had a minimum peak-to-valley resolution of 150nm, approximately λ/4. The resolution of the FRT method was 15nm.

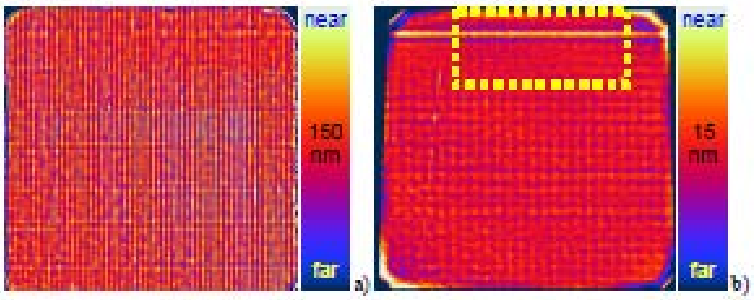

Fig. 4. Fine structure profiling using a) grating interferometry and b) FRT

The applications for such a system are really extensive. The system is very versatile in that it only needs an LCD screen and a camera to use. It could be implemented using laptops or cell phones that have a built in fixed camera very easily. Due to the fact that 4 successive images are being taken, it is susceptible to vibrations as the imaging geometry is likely to change in between the 4 measurements. The system can easily to be scaled to examine large scale optics and coatings. Car manufacturers could easily implement a system such as this to determine the smoothness of paint coatings or verify the shape and surface of precision parts such as a piston. A similar system has been developed by Peng Su *et al.* known as SCOTS [4]. It uses a scanning line technique instead of sinusoidal fringes, but the method is very similar. It takes thousands of images instead of just 4 and has been used primarily in testing of large optics such as telescope mirrors. The accuracy of SCOTS and FRT are both highly dependent on the accuracy of the calibration done beforehand. It is very sensitive to the imaging geometries used and when scaled down for small optics the distances must be measured much more accurately.

References:

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4. Su, Peng, et al. "SCOTS: A computerized reverse Hartmann test." *submitted to Optics Express* (2010).