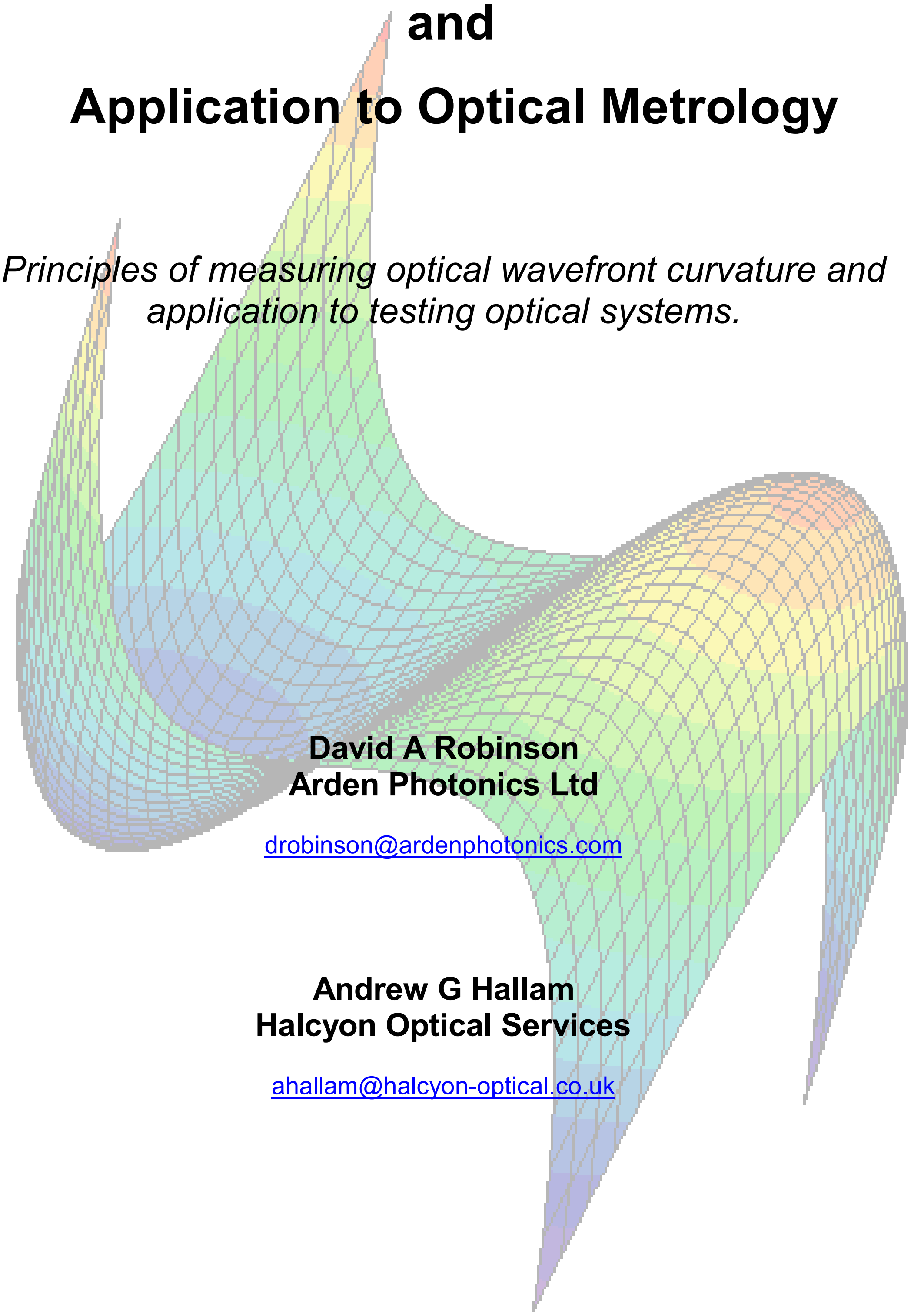
Wavefront Curvature Sensor Technology
and
Application to Optical Metrology

Principles of measuring optical wavefront curvature and application to testing optical systems.



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Overview

Wavefront curvature sensing is a powerful technique with applications in many fields of optical metrology. It offers high sensitivity, wide dynamic range and flexible spatial resolution characteristics.

Despite its many advantages, curvature sensing requires measurement of the intensity profile in two different planes along the optical axis and previously this had the disadvantage of having to mechanically move the detector, or collection optics. This meant that implementations of curvature sensing were less reliable and robust than other methods.

The AWS-50, the only commercially available wavefront *curvature* sensor, overcomes all of these problems by incorporating a patented device known as the Image MultiPlexing (IMP™) diffraction grating. The IMP™ is a quadratically distorted diffraction grating designed to simultaneously produce the two images of the wavefront required for curvature sensing, and to spatially separate them onto a single image plane. The image sensor in this case is a CCD array. The two intensity profiles of the beam can then be recorded and analyzed with no need for moving parts.

Wavefront sensing has been used for wavefront measurement in astronomical applications for many years. More recently, interest has grown in the use wavefront sensing in applications as diverse as ophthalmic surgery, optical metrology, adaptive optics, laser beam profiling, and the measurement of precision mechanical components such as wafers and automotive parts.

Wavefront *curvature* sensing is an important technique in this field, and has been implemented in adaptive optics systems. By contrast to the Hartmann type systems which measure local tilts on the wavefront, *curvature* sensing involves measuring the intensity profile of two images of the wavefront, spatially separated along the axis of the beam. This is achieved by the IMP™ quadratic diffraction grating which has the unique ability to sample the wavefront at two planes and form two images side-by-side on a CCD camera, as shown by the blue rays and red rays in Figure 1.

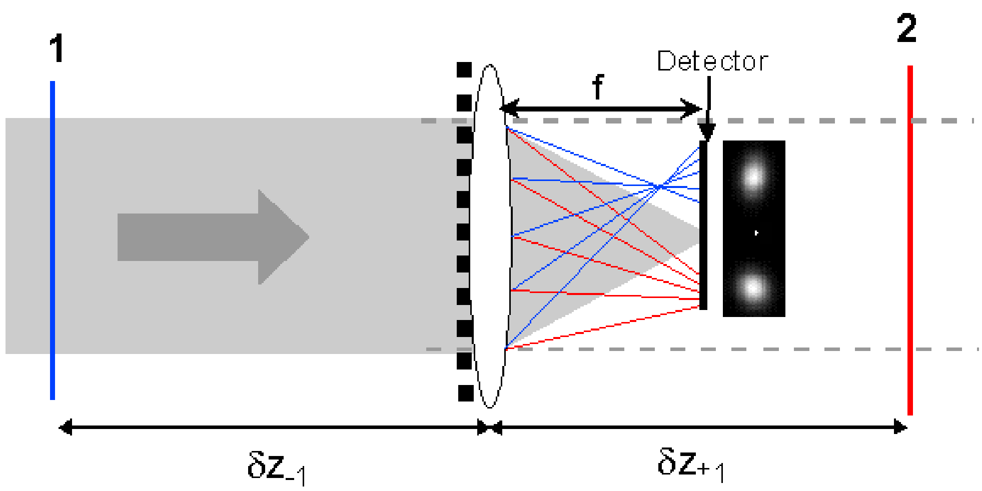


Figure 1. Optical arrangement in the AWS-50, with quadratic grating.

Then, by comparing the difference in intensity between the two images, on a point-by-point basis, the axial derivative of intensity over the image plane, $\partial I(x, y; z)/\partial z$, can be determined. The wavefront shape, $\phi(x, y; z)$, can then be reconstructed by solving the Poisson equation, shown below[1]:

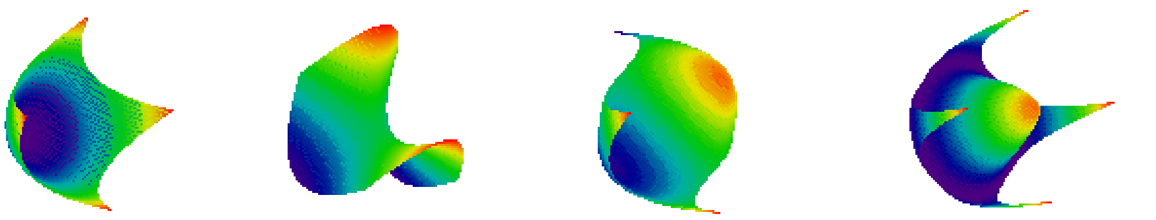
$$\nabla^2 \phi(x, y; z = 0) = -\frac{1}{I_o}\left[\frac{\partial I(x, y; z)}{\partial z}\right]_{z=0} \qquad (1)$$

From (1) it can be seen that the difference in intensities between the two images is, in fact, proportional to the second derivative of the wavefront shape, $\phi(x, y; z)$, and so the technique is one of *curvature* sensing, in contrast to the Hartmann sensor that measures the first derivative of the wavefront, known as tip and tilt.

Zernike Polynomials

The actual shape of an aberrated optical wavefront is often represented mathematically by a particular set of functions known as the Zernike polynomials. These polynomials are the same form as the types of aberrations often observed in optical tests and they may be readily calculated from the reconstructed wavefront described above. When higher-order aberrations are not present, the first few Zernike polynomials have close correspondence to the Seidel aberrations of traditional third-order optics, such as astigmatism, coma and spherical aberration. It should be noted, however, that higher-order Zernike modes also contain a component of the lower-order aberrations of the same type. For example, Z_5^1, which is secondary coma, also contains information on primary coma and so, if this term is non-zero then the equality of the Seidel and Zernike terms for primary coma is no longer maintained[2]. Combinations of higher-order Zernike polynomials are, however, a very powerful means of representing the exact shape of a distorted or aberrated wavefront.

The AWS-50 typically computes coefficients for the first ten Zernike polynomials. A few low-order Zernike polynomials are shown in Figure 2, below.



Z_2^0 Defocus $\quad$ Z_2^2 Astigmatism $\quad$ Z_3^1 Coma $\quad$ Z_4^0 Spherical aberration

Figure 2. Graphical representation of some low-order Zernike Polynomials

Applications

Curvature sensing has many benefits in optical metrology. Because it is fast, insensitive to vibration and doesn't require a highly coherent light source it can be introduced into environments where interferometers cannot be used, such as on the shop floor in the optical manufacturing environment. It enables manufacturers of a wide range of precision optical and mechanical products to improve quality by taking high accuracy measurements wherever they are needed. Typically, interferometers require stable environments and controlled conditions so they are usually consigned to a measurement or standards lab.

Because all the data acquisition can be acquired in a single frame, it means that the AWS-50 is capable of real-time measurement, is insensitive to vibration, and is robust and compact in size.

Figure 3 shows a comparison of the first few Zernike modes computed from an interferometric measurement of a surface and the corresponding measurements made using the AWS-50 wavefront sensor. It can be seen that the two sets of data agree with each other to within the experimental error of the measurements.

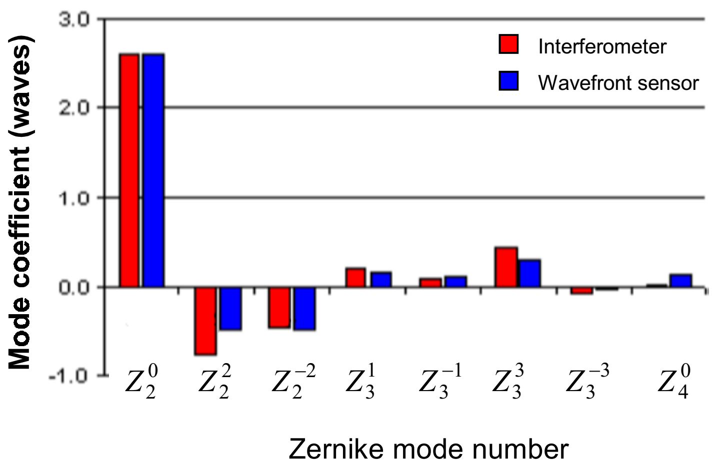


Figure 3. Comparison of Zernike coefficients measured by Interferometer and Wavefront Sensor

Applications of wavefront curvature sensing include such diverse fields as optical astronomy, ophthalmometry, laser beam profiling, optical component testing, and microscopy.

Wavefront curvature sensing is particularly applicable in the field of adaptive optics[3] where the components of an optical system are actively adjusted to maintain high image quality. For example, the resolution of ground-based telescopes is highly dependent on the amount of atmospheric turbulence present, as this causes distortion to the wavefront and hence a reduction in image quality. In an adaptive optical system the distortion is directly measured by a wavefront sensor which then provides a control signal for corrective optics such as deformable mirrors. Such systems typically have to work at speeds of several hundred Hertz in order to keep up with rapid changes in the atmosphere.

Another adaptive optic application is in the control of the wavefront in high energy lasers where thermal distortion of the gain medium can lead to hot spots and subsequent damage to the laser optics. Wavefront sensing enables the wavefront to be actively controlled and thus avoid potentially catastrophic failure.

In ophthalmometry, wavefront sensing is increasingly being used to characterise higher-order aberrations in the human eye, providing vital information for corrective laser eye surgery[4]. The use of Zernike polynomials as a means of describing the measured aberrations of the eye was preferred over traditional Seidel functions by a special task force of the Optical Society of America in1999[5].

Laser beam profiling is another area in which the AWS-50 wavefront curvature sensor has applications. Information on the laser beam wavefront is valuable to users of industrial laser users, because it enables them to optimize the brightness and performance of their lasers. An enhancement of the IMP grating which is currently under investigation should enable the system to produce real time M-squared measurements, which will give users valuable information on the optical alignment of their lasers, and the focussing of the output beam. The measurement is again performed in real time with no moving parts so brings particular advantages to pulsed lasers and lasers where the beam characteristics are changing, such as during warm-up.

Wavefront sensing has also been applied to improving image quality in confocal microscopy where the sectioning property of such microscopes means that inner layers of an object are viewed through outer layers, leading to wavefront distortion. An adaptive optic system utilising a piezoelectrically controlled mirror to provide tip and tilt correction has recently been shown to improve image quality in a confocal microscope quite dramatically[6].

Wavefront sensing also has application in testing individual optical components, such as lenses and mirrors. This information can lead to reduced development times, reduced component cost and improved optical performance. Typically the wavefront reflected from a surface under test is compared to that from a reference surface enabling wavefront errors, or aberrations, to be determined.

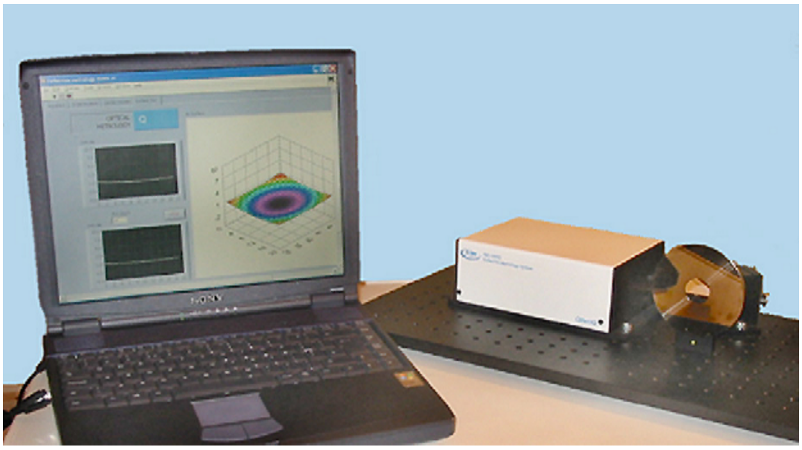


Figure 4. AWS-50 testing flatness of magnetic storage disc

Summary

Wavefront curvature sensing, as implemented in the AWS-50, for the first time offers all the advantages of high accuracy, real-time measurement, along with the design flexibility for high dynamic range for measurement of optical systems, high spatial resolution for beam profiling, or large apertures for testing mechanical components.

References

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