2 Surface profilometry: state of the art

The evolution of surface profilometry measurements has closely followed the increase in computing capabilities over recent years. Cheaper computing power has allowed huge amounts of data to be processed, and visualization tools to be developed to interpret this information. This situation has led to the blooming of a variety of techniques for collecting the data to be processed in order to achieve the final profile of the surface.

Some of these techniques have existed for a long time and have been greatly enhanced with the transformation from screens and photographic plates to digitized intensity patterns, and with the advent of linear encoders and piezoelectric drives. This is the case with deflectometric and interferometric techniques, for example. Some other techniques have taken advantage of these new technologies in order to establish new kinds of profilometry measurements, this being the case of confocal microscopy or time-of-flight profilometry.

As these techniques are developed and enhanced, they are used in industries involved in non-destructive measurement of surfaces, such as the semiconductor industry, which started it all. However, not only the semiconductor industry or the precision optics manufacturers benefit from the development of new profilometric techniques. Many companies far from the optics field are becoming aware of the possibility of improving their processes through non-contact profilometric measurements. The wide variety of techniques available offer solutions for a number of different measurement problems; however, this variety makes an adequate selection of the measurement technique one of the key steps for the success of the application.

A number of books on optical metrology are now available [Gasvik 1995] [Malacara 1992], so the purpose of this chapter will be to provide a general description of some usual profilometry techniques, and of recent developments in each of these. In order to keep the length of this chapter within reasonable limits, we will need to restrict ourselves to profilometry techniques directly related to profilometry of reflective optical quality surfaces, the subject of the present work.

2.1 General review

A test of the most representative techniques among the wide range of described profilometry setups will be presented. Starting with a global overview of profilometry techniques quite different of the measurement of reflective optical quality surfaces through deflectometric techniques, we will gradually come closer to our field of application. Some optical techniques which we believe to be especially relevant in the profilometry of reflective surfaces will deserve lengthier comment in following sections.

Although mainly applied to three-dimensional profilometry of diffuse objects, it is worth starting our review of profilometry techniques mentioning the existence of a whole generation of optical profilometers based on projection of gratings (typically with sinusoidal transmittances) onto the object to be profiled [Hailoua 1985]. A set of enhancement techniques and variations have been described, including fringe modulation analysis combined with phase stepping techniques [Su 1993], and Fourier transform approaches [Yi 1997]. In these enhanced techniques, typical accuracies are around 0.1mm in fields of view around 300x300mm..

Holographic and speckle techniques based on the interference between two slightly different waves are also far from our field of application, as they are usually applied to the measurement of surface deformations and vibrations [Rastogi 1994]. They might be considered differential profilometers, in the sense that they measure the difference between two states of the sample by recording the interference fringes resulting from the superposition of light coming from the sample in each of these two states. We are aware that surface profiles have been obtained through these techniques, by introducing a known amount of displacement between both superimposed waves. Accuracies of 3µm in height in 25x25mm samples have been reported [Lulli 1996].

Optical microscopy is another classic non-contact technique in surface profile measurements. In recent years, Scanning Electron Microscopy (SEM) and scanning probe microscopes (Scanning Tunnel Microscopy (STM) together with Atomic Force Microscopy (AFM)) have become a commonplace technique in the measurement of surface parameters. Although studies do exist that apply STM to the analysis of conductive optical quality surfaces, such as gold surfaces [Dragoset 1986], AFM is best suited to studying optical surfaces due to their non-conducting nature [Binnig 1986]. Typical height sensitivities using AFM are in the angstrom range for sample areas of 40µmx40µm. The Nanoscope II© AFM from Digital Instruments© has been reported to have 0.1nm height sensitivity and lateral sensitivities in the order of a few tenths of a nanometer [Bennet 1993].

Another set of microscopy techniques is based on point-by-point focusing of the surface, with some particular additional steps taken in order to obtain the profile of the surface of the sample properly. Confocal microscopy is the main representative of this group, and will be considered at some length in Section 2.2. Dynamic focusing techniques involve splitting the illumination beam through a prism, and focusing each of these fans onto a pair of faceted detectors whose differential signal indicates whether the surface is in or out of focus. This signal is fed back to a motor which varies the lens position (Fig.2.1.1). When the beam is focused onto the surface, the signals from both detectors are equivalent and the surface height at the given point is recorded. Typical accuracies are around 2µm, in ranges depending on the number of measurement points used. As the lens must be focused at each data point, the time taken in the measuring process must be taken into account.

Fig.2.1.1: Setup for dynamic focusing profilometry [Creath 1992]

Mechanical profilers have been used and developed over the last 50 years. The operating principle is quite simple: a stylus runs over a surface, and its height displacements are recorded via a capacitive transducer, yielding a profile of the surface. However, the need for a physical interaction with the surface (the stylus must be placed in contact with the surface) is its main drawback, as a whole set of non-contact optical techniques are being put on the market. This scanning involves performing precise lateral displacements, usually in the range of 0.1µm [Song 1991]. Vertical sensitivities at 0.1nm, which is considered the theoretical limit for stylus profiling, have already been reported [Bennet 1989]. Commercial equipment, like Tencor Instruments© Alpha Step© 100, is claimed to have 10nm accuracies with maximum scan lengths of 5mm. Typical analysis times are said to be around 10 minutes.

Another group of techniques is based on reflectometric measurements. These are non-contact profilometry techniques based on the triangulation principle. A laser source is focused onto the surface being measured and its reflection is imaged onto a position-sensitive detector (PSD). Whenever there are small deviations on the surface, a displacement on the image may be measured on the PSD yielding the value of the displacement on the surface. This value may be shown to depend only on the angle between the illumination and detection optical systems, and on the lateral magnification of the observation optical system. When applied to diffuse objects, the resolution of the technique is limited by the speckle patterns on the image plane [Dorsch 1994]. Although scanning of the surface is unavoidable because the measures are taken point by point, the technique may be applied to reflective objects well over the meter range [Thibault 1997]. This has led to the technique recently being proposed as a three dimensional space perception system for blind people [Farcy 1997]. Opmetec© markets one triangulation system which is said to achieve maximum vertical accuracies of 1nm through software compensation along a 2μm sample. It is also claimed to achieve accuracies of 6μm along a 150μm sample. Systems not using the "software compensation" (MicroPhotonics'© Proscan© 1000) claim to have 10nm vertical resolution in measurement ranges of 160μm, and 6μm vertical resolution in 80mm measurement ranges.

Another set of techniques that are to some extent connected with reflectometric methods is based on time-of-flight measurements. These systems measure the time delay of the signal emitted from the source when, after reflection on the sample surface, the signal is received in a detector. They have been conventionally applied to two-dimensional ranging of target scenes [Hill 1995], with reported accuracies of a few centimeters in ranges of 2m. However, millimeter accuracies have recently been reported [Maata 1997]. Commercial systems based on the time-of-flight principle are available from the Fraunhoffer Institute of Physical Measurement Techniques©. This system is claimed to achieve 0.1 to 1mm accuracies in samples ranging from 0.2 to 20m. Working distances of a few meters, typical of triangulation systems, are used.

As a general review, a graphical comparison of the vertical and horizontal resolutions of Scanning Probe Microscopes, stylus and optical profilers may be seen in Fig.2.1.2 [Creath 1992]. The categories are quite general, but give a reasonable image of the state of the art in surface profilometry.

The techniques closest to ours will be the ones commonly used for testing optical quality surfaces: interferometric and deflectometric techniques. Interferometric techniques are based on the superposition of two wavefronts, with the local phase

Figure 2.1.2: Comparative measurement ranges for Scanning Probe Microscopes, stylus profilers and optical profilometry techniques

differences resulting in a fringe pattern. The accuracies, requirements and recent developments of interferometric techniques will be studied in Section 2.3, where a non-intensive overview of some experimental setups will be presented. Deflectometric techniques, described in Section 2.4, rely on the interaction of the wavefront coming from the sample with a mask placed in its path. From the pattern obtained on the observation plane, quantitative information on the wavefront aberrations and the surface profile may be obtained.

2.2 Confocal microscopy

Of all approaches to optical profilometry, confocal microscopy comes forward as the non-contact profilometry technique which most closely competes with the capabilities of mechanical stylus profilers, because of its accuracies and large measurement ranges. The relatively early stage of its development and the active research being carried out in the field also promise further developments and applications for a technique whose capabilities have already reached the market.

Profilometry through depth-from-focus measurements can be achieved in a different way from that of the dynamic focusing techniques described in Section 2.1. Instead of displacing the focusing system in one direction or another depending on the detected signal, we could measure the light intensity distribution obtained on a set of pre-determined planes along the optical axis of the system. By software treatment of the intensity patterns obtained, the particular plane where the system was focused may be determined, yielding the measurement of the height of the surface from the reference plane at that particular point. If a setup with high sensitivity to defocusing is implemented, the resolution achieved in vertical displacements seriously competes with many existing commercial stylus profilometers, with the further advantage of its non-contact nature.

Confocal microscopy techniques are based on this measuring principle, and a general setup is presented in Fig.2.2.1. A pinhole or slit is imaged onto the surface to be profiled; it is an optical path $d_{PATTERN}$ away from the focusing system. The pinhole (termed pattern in Fig.2.2.1 for reasons that will soon become evident) is then imaged onto the surface and a CCD camera is placed a distance d_{IMAGE} from the focusing system in order to register the pinhole's Airy intensity distribution. A set of intensity distributions are detected in this way at varying object distances, and software algorithms are implemented that allow the reconstruction of the so-called "focusing function" of the surface. The best focusing plane allows the displacement from a reference plane of each tested surface point to be measured. Quite often, an array of pinholes (the "pattern" in Fig.2.2.1) is imaged simultaneously onto the surface in order to improve the speed at which measurements are taken. 0.1µm accuracies in polished samples 400µm wide have been reported using this system, with lateral resolutions of 12µm [Fieguth 1994]. Using refractive microlens arrays in order to improve the measurement speed has also been proposed [Eisner 1998].

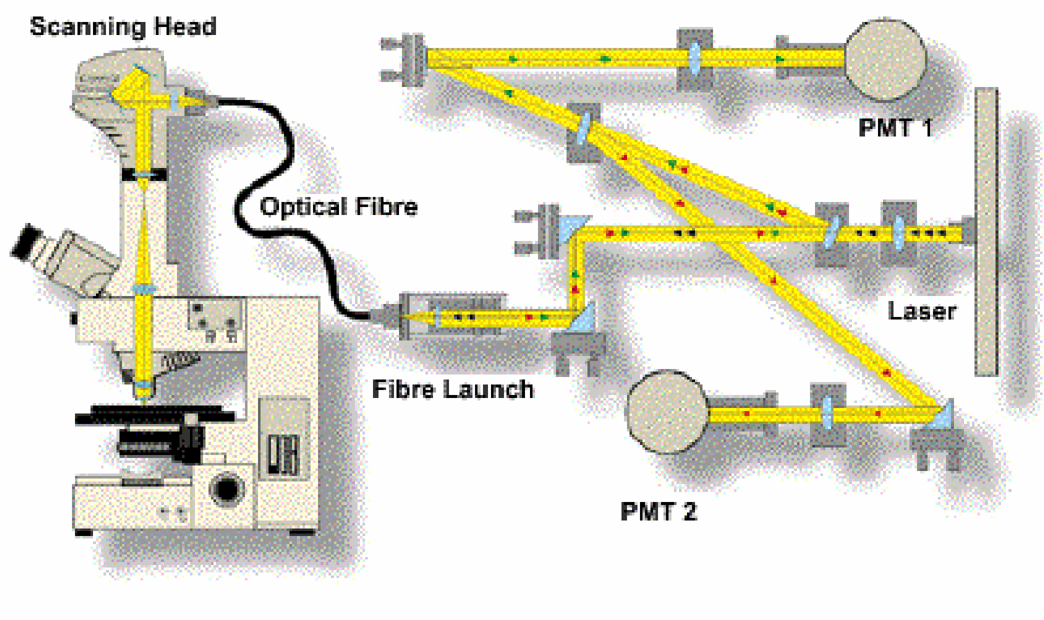
Further improvements to the technique have been proposed through the use of super-long working distance (SLWD) microscope objective lenses. Measured surface slopes up to 45° have been obtained with an accuracy of 10nm in vertical displacements and 1 µm spatial resolution [Laguarta 1998]. Interesting improvements to the accuracy of the technique may be achieved on smooth surfaces through the tilt of the sample and the study of the resulting intensity patterns in the CCD array [Conchello 1997].

Fig.2.2.1: Experimental setup for confocal microscopy

Although the technique is a subject of active research, commercial confocal microscopy equipment is already available. Technical Instruments Company© features both a laser confocal microscope with resolutions in the nanometer range, and a white light confocal microscope which delivers real-time imaging of sub-micron structures. Kovexvision© markets a reflection confocal microscope said to be specifically designed for material industries, with sub-micrometer axial resolution.

One very interesting approach to confocal microscopy has been taken by Optiscan©, which has developed an optical system (U.S.Patent 5.120.953) claimed to be adaptable to most existing commercial microscopes and to dispense with the need for mounting lasers and detectors onto the microscope (see Fig.2.2.2). It is claimed to achieve lateral resolutions of 220nm and axial resolutions of 450nm, with fields of view of around 100µm. A laser source at the user's choice lights the sample via an optical fiber, which also provides the confocal pinhole and the return path for reflection techniques. Hamamatsu© photomultiplier tubes (PMT) are used as detectors; a transmission detector not pictured in Fig.2.2.2 is also available.

Fig.2.2.2: Optiscan confocal commercial system (from Optiscan web pages)



2.3 Interferometric techniques

Except for the group of grating projection techniques and the STM and AFM techniques mentioned in Section 2.1, the techniques presented up to this point sample the surface to be profiled point by point. Interferometric techniques have the advantage of capturing data from the whole field of view under measurement in a single shot, with vertical accuracies only achieved for scanning probe microscopes. Their non-contact nature and easy implementation for on-line process control in some industries (for instance, precision optical manufacturing or wafer inspection in the semiconductor industry) has led to the development of commercial equipment closely following the active research being done in the field.

The measurement principle is very well known. A reference coherent beam overlaps in the observation plane over a beam carrying information on the surface being measured in such a way that interference fringes appear. The phase differences in the reflected beam can so be measured, and translated into height information, yielding the profile of the surface. Different configurations are available for the interferometer, depending on the properties of the sample and the magnification desired. Interferometric microscope objective lenses play the key role in this kind of profiler. Fig.2.3.1 shows the most usual configurations, which are selected according to resolution and the required working distance. Michelson configurations require long working distances and are used for low magnifications. Mirau objectives are used in middle-range magnifications, and Linnik configurations are usually used in high magnification systems, because of the very short working distance required. Fizeau objectives are used in a wide range of magnifications, but the required working distance must allow a reference surface to be placed in the light path.

Figure 2.3.1: Typical interferometric microscope configurations [Creath 1992].

An extensive listing of the configurations described in the literature is not within our scope in the present Section. As an example, and because of their great accuracies, we will mention polarization interferometers, in which a Wollaston prism is used as a beamsplitter prior to a microscope objective focusing on the surface (Fig.2.3.2). The test surface rotates around one of the two focused beams, which acts as a reference, allowing high accuracy height measurements at the other focused beams. Subangstrom accuracies are typical values. Some configurations allow linear scannings for the profile of the surface rather than circular paths.

Figure 2.3.2: Setup for polarization interferometers [Creath 1992].

Phase-shifting techniques will be described at some length in Section 5.2, when dealing with accuracy improvements in the Ronchi deflectometry technique. Let's just point out that in this enhancement techniques a set of fringe patterns are registered with known phase delays between them. As the fringes follow a known sinusoidal pattern, data from the whole measurement field and not only fringe maxima may be used in the whole set of measurements, so the height values may be obtained with higher accuracy [Creath 1988]. Accuracies of $\lambda/100$ are typically obtained when applying this technique. A Fourier description of the technique allowing the study and treatment of some systematic errors in the process [Freischlad 1990], and general techniques for formulating phase reconstruction algorithms tailored to each experimental setup have been developed from different approaches [Surrel 1996] [Phillion 1997].

Another interesting improvement which has been proposed is the use of Moiré techniques in interferogram analysis. The Moiré effect is an intensity beating appearing in the superposition of slightly different gratings (Fig.2.4.1), which is the basement for a deflectometric measurement technique (see Section 2.4.1), but may also be used in order to accurately extract phase information about the measured wavefront. If the fringes obtained from the interferometric setup are projected over a Ronchi ruling, or a reference wavefront fringe pattern, Moiré patterns appear in the register, which allow the phase of the measured wavefront to be extracted. Furthermore, phase-shifting schemes based on ruling displacement may be implemented in Fizeau interferometers [Dorrío 1995]. Another approach to the technique is the superposition of two slightly different interferograms, yielding Moiré fringes without any intervening Ronchi ruling. This technique has been applied to collimation testing using shearing interferograms [Choi 1995].

One of the main drawbacks of interferometry techniques is their inability to measure in the presence of height discontinuities in the measurement field. When the phase values are obtained and a discontinuity in the fringe pattern appears, there is no way of knowing the number of fringes lost in the discontinuity. If we use a light source with short coherence lengths (incandescent bulbs, LED's), the high spectral bandwidth of the source would yield interference patterns only when the optical path difference between both arms of the interferometer was close to zero. So the sample might be displaced along its normal vector until the interference pattern appeared, yielding the step height. Although this system may be used for point-by-point profilometric measurements, it is usually implemented together with a common phase-shifting interferometer in order to solve the phase indeterminations of the latter. White light interferometry has also been successfully applied to the measurement of rough surfaces [Caber 1993], and multiple-wavelength interferometry with modulation in light frequency and intensity has been proposed as a way of obtaining phase-shifting measurements without the need for piezoelectric transducers [Calatroni 1993]. Measurements of step heights through interferograms at two different wavelengths with $\lambda/1000$ accuracies have also been reported [Creath 1987].

Its commercial and academic interest has meant that a wide range of literature concerning interferometry and related techniques is now available [Malacara 1992] [Malacara 1998]. To cite just some of the latest relevant reports of which we are aware, some recent developments involve Mirau configurations with phase-shifting control which automatically amends the phase-shifter errors, yielding height resolutions of 0.3nm with repetitivities of 0.5nm [Ding 1996]; setups which combine confocal and interferometric microscopy in a single instrument through varying the coherence properties of a semiconductor laser source, which are controlled by its injection current [Rea 1996]; or interferometric measurements of cylindrical surfaces, through a subaperture test with a connecting algorithm [Wan 1993]. New improvements to the technique are reported almost monthly, and a series of workshops and meetings exclusively devoted to interferometry and related methodologies is held yearly.

The number of commercially-available machines is also considerable. The Wyko© TOPO© interferometric profiler uses white light illumination and interchangeable Michelson, Mirau and Linnik configurations in order to achieve different magnifications ranging from 1.5x to 200x. It is said to achieve 0.01 repeatabilities with allowed maximum surface height changes of 15μm using the white light configuration. It must be stated that under monochromatic illumination this value falls to 0.162μm for the same instrument. Lateral resolutions range from 0.35μm to 27μm, and measurement times are as low as 465ms for three-dimensional profiles. Up to fourteen different interchangeable interferometric objectives are available for this instrument.

The Zygo© Maxim GP© interferometric profiler combines Michelson and Mirau lenses with magnifications ranging from 2.5x to 100x; subangstrom resolutions and repeatabilities are also claimed for this equipment, where the coherence of the white light source is controlled through interchangeable filters of variable bandwidth. In this case, six different interferometric objective configurations are available.

2.4 Deflectometric techniques

Although interferometric techniques give very high accuracies, they have inherent problems for measuring strong slope variations within their field of view at a single shot. This field of view becomes too small if the surface to be tested is a few square centimeters in size. Deflectometric techniques give topographic profiles of surface samples of sizes up to several meters in diameter, in turn paying the price of accuracies under those of interferometry. Here we will describe the three main deflectometric techniques, that is, Moiré, Hartmann and Ronchi techniques.

2.4.1.- Moiré techniques

Moiré techniques are related to the fringe projection techniques mentioned in Section 2.1 in order to profile diffusive objects. The latter, dating from the 1950's, may not be considered deflectometric measurements as far as no ray-deflection measurements or wavefront sensing is carried out, although topographical information on the sample is obtained.

Moiré deflectometry is a novel technique dating from the mid-80's, based on the Moiré effect. This effect takes place when two gratings of square or sinusoidal transmittance of equal or unequal periods are placed one against the other, yielding lines which are slightly tilted in respect of one another (Fig.2.4.1). A beating in the resulting observed intensity pattern is observed.

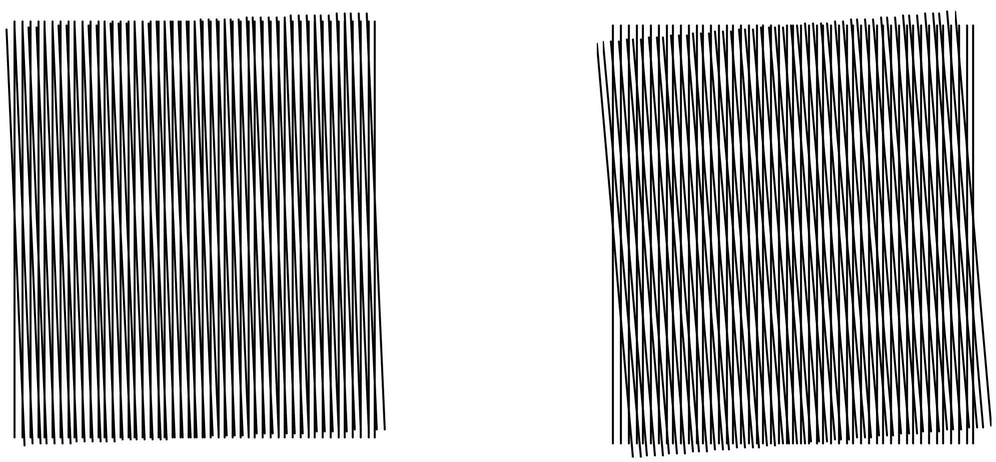
A geometrical analysis shows the Moiré fringes to be straight lines with periods $T'=T/\theta$, with θ being the inclination angle between both rulings, and T the ruling period. Fig.2.4.1a shows Moiré fringes with twice the period of Fig.2.4.1b, corresponding to the relative angular tilts introduced.

The setup for Moiré deflectometric measurements involves a collimated light source and a pair of Ronchi rulings (Fig.2.4.2). If the beam is not fully collimated, distorted fringes will be obtained. Small deflections of ϕ rad in the perpendicular direction to the first grating bands displace the straight fringes a given amount which may be measured, yielding a quantitative measurement of ray deflection through

$$\phi(x,y) = z'\frac{\theta}{d} \qquad (2.4.1)$$

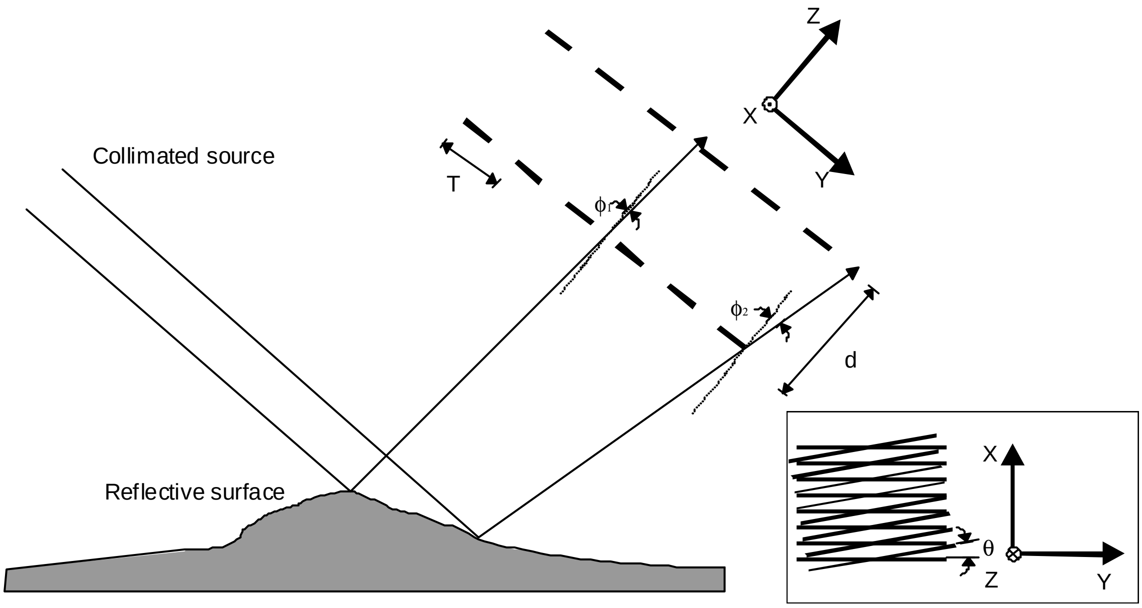
Fig.2.4.1: Moiré effect with gratings of equal period a) Rulings tilted 2.5°; b) Rulings tilted 5°

(a) (b)



where z' is the fringe displacement from its ideal position, θ is the relative tilt between rulings and d is the distance separating both rulings. This is the so-called finite fringe configuration; in the infinite fringe configuration both rulings are parallel (θ=0), and contour maps of ray deflections at steps T/d are obtained, T being the period of the ruling [Kafri 1985].

Fig.2.4.2: Typical configuration for a Moiré deflectometer



Further improvements to the technique have been proposed. Fourier treatment of Moiré patterns in three-dimensional spaces that allow the use of spatial filtering techniques [Parker 1991], the use of sinusoidal transmittance rulings in order to reduce diffractive effects [Keren 1985], or phase-shifting schemes [Pfeifer 1995] have been reported. Point laser and point white-light sources configurations combined with retroreflector systems have been tested, giving source and detector in the same position in the system [Liasi 1994]. Recent developments point towards automated measurement through algorithms that estimate fringe directions locally [Canabal 1998].

The technique has been applied to a set of measurement problems, from refractive index gradients to density field analysis in fluids or transient thermal lensing [Kafri 1985]. The technique has also been used for determining optical properties of lenses, such as measurements of non-paraxial focal lengths [Glatt 1987], or topographies of aspherical contact lenses [Rottenkolber 1996].

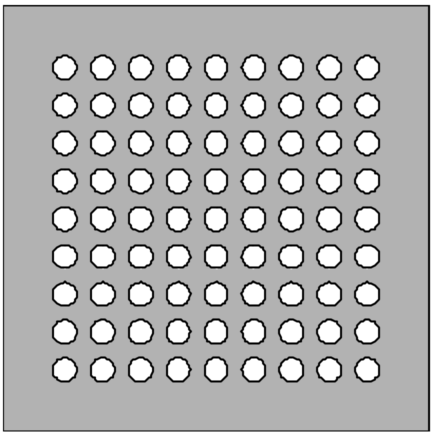
Because of their ability to detect variations in fields causing ray deflection, their low noise and vibration requirements, and their real-time performance, Moiré systems are being incorporated into industrial control systems. Electronic Packaging Systems Ltd.©'s LineMoiré© system is used as a stand-alone or in-line automatic flatness inspection system. Innomess© features a system for detection of defective floating glass zones. Rotlex© Class-Pro© is used in the mapping of power and cylinder distributions of multifocal progressive lenses, with a continuous measurement over the whole lens area. It achieves radius measurements from -7.00D to 7.00D in 0.06D steps. The same company offers products for measuring topographies of toric soft lenses or lenses polished for only one surface (semi finished lenses).

2.4.2.- Hartmann test technique.

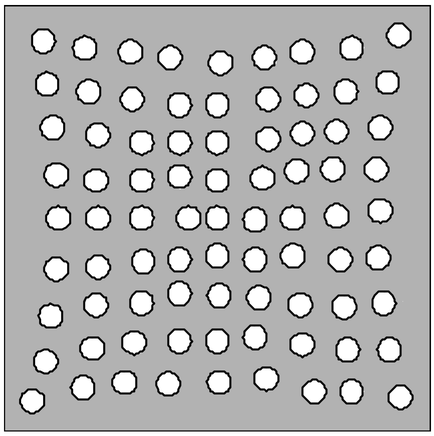
If a test of a given shape is placed in the path of a converging wavefront, and the intensity pattern containing the shadow of the test is registered, these shadows will be related to the transversal aberration values present in the wavefront, which give the slope of the wavefront in each given position. Local wavefront errors may therefore be measured. Hartmann and Ronchi test techniques follow this approach, and have been described through the same mathematical theory [Cordero 1992].

Fig.2.4.3: a) Hartmann test as a squared pattern of holes; b) Typical recorded shadow pattern. Aberrations in the wavefront and hole sizes have been rather exaggerated.

(a)

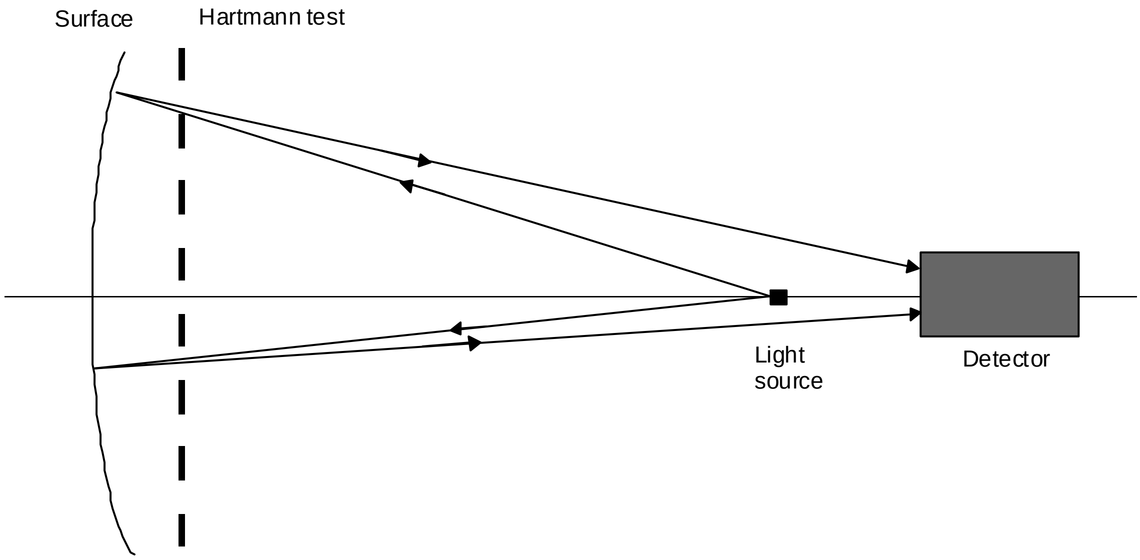


(b)



The Hartmann test consists of an array of holes (which can be placed on the screen in radial, helical or squared patterns [Gozheil 1992]), whose shadows provide a measurement of the aberrations present in the wavefront, as the deviation from expected slope variations may be measured (Fig.2.4.3). These measurements of transversal ray aberration on the observation plane may be related to wavefront aberrations [Rayces 1964] yielding a reconstruction of the wavefront. This system is used for the measurement of the residual aberrations of primary telescope mirrors, with the Hartmann test placed at the exit pupil of the mirror and the observation plane placed close to the center of curvature of the mirror (Fig.2.4.4). In this way, small local deviations of the surface slopes may be detected. Using square patterns for the hole distribution, better suited to the CCD detectors used today, surface deviations as small as 0.1µm may be detected [Gozheil 1992].

Fig.2.4.4: Conventional Hartmann test setup



Modified Hartmann setups have been used to measure power and residual astigmatism profiles of spherical reflective surfaces [Arasa 1996]. Another modified Hartmann setup with the holes replaced by a circular scanning laser beam has mapped some optical characteristics of progressive addition lenses [Castellini 1994]. The measured Hartmann pattern may be geometrically transformed to give an equally spaced grid, which through a bandpass filter may be transformed into two orthogonal cosinusoidal fringe patterns modulated by the transverse ray aberration, which may then be processed through interferometric techniques [Servín 1996]. Differential Hartmann test configurations, use of phase masks to give better results in low illumination conditions, and use of Fourier transform methods common in interferometry have also been proposed [Roddier 1990].

The Hartmann test technique has lately been shown to be especially well-suited to the newly developed adaptive optics technology. A two-dimensional array of lenslets at the holes of the Hartmann test divides the wavefront impinging on them into multiple focal spots and the subaperture sampled by each lenslet is focused on a detector. The lateral position of the focal spot depends on the local tilt of the incoming wavefront, so real time measurements of wavefront gradients may be achieved [Schmultz 1996]. Accuracy analysis in the imaging of astronomic faint objects [Cao 1994] and studies of the influence of misalignment errors in the measured data have been reported [Pfund 1998]. This kind of sensors, called Shack-Hartmann sensors, have recently reached the marketplace as portable light analysis systems. WaveFront Sciences© CLAS-2D© system is claimed to have accuracies of 50nm with dynamic ranges over 100µm; measuring times range from 17ms to 0.1ms in the profiling of light beams.

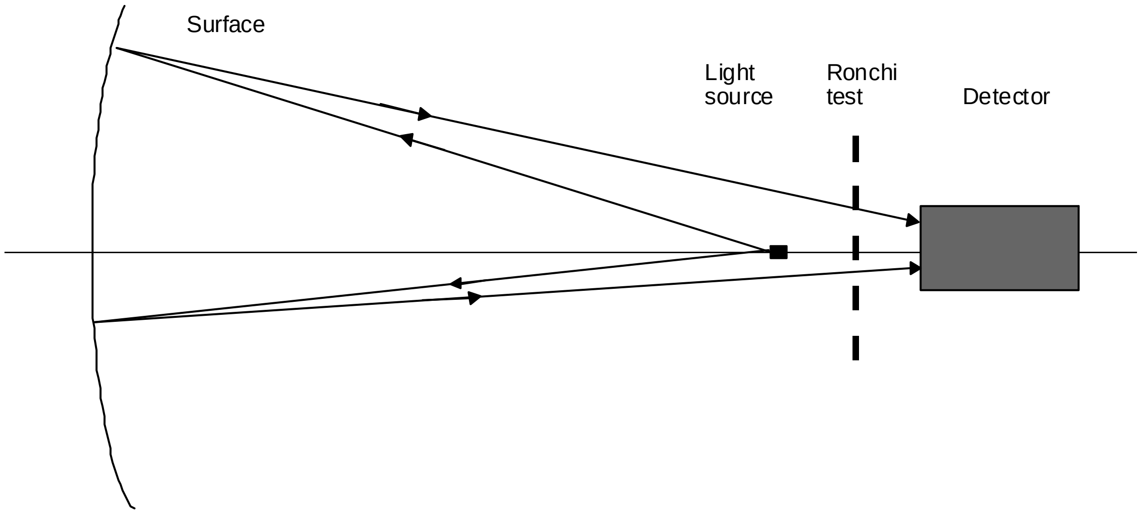
2.4.3.- Ronchi test technique.

The Ronchi test technique has long been used by telescope makers in order to qualitatively correct the aberrations present in their systems during manufacture. As previously mentioned, this may be explained through exactly the same mathematical theory as the Hartmann test. In this case, however, instead of a pattern of holes a set of parallel stripes giving a square-wave transmittance profile is used.

The Ronchi test enhances one of the drawbacks of the Hartmann test: sampling the wavefront only along discrete points may prevent some discontinuities in the wavefront from being measured. Continuous measurement along the Ronchi ruling stripes avoids this possibility. However, measurements of transverse ray aberration must now be carried out in two orthogonal positions of the Ronchi ruling, as the test is insensitive to transverse aberration measurements along the direction of the stripes on the ruling. Furthermore, some other improvements concerning surface sampling which could not be implemented in the Hartmann test may be implemented in the Ronchi test (see Section 5.3).

Conventional Ronchi setups measure transverse ray aberration in two orthogonal directions at the plane where the Ronchi ruling is placed, thus obtaining the wavefront aberrations and slopes on that plane. As may be seen in Fig. 2.4.5, the Ronchi test setup differs from that of the Hartmann test in the position of the test, which is now placed close to the center of curvature of the surface being tested. The two techniques also differ in the surface reconstruction technique: while in the Hartmann test the wavefront is reconstructed through integration of the data points, in classical Ronchi test setups polynomial fitting (usually using Zernicke polynomials) is used.

Fig.2.4.5: Experimental setup for the Ronchi test



Although this deflectometric approach is commonly used, with the observed fringes being shadows of the ruling stripes, when using high frequency rulings the Ronchi test may be considered to be a lateral shearing interferometer. All topics connected with the use of the interferometric (diffractive) or deflectometric (geometrical) approaches are considered at length in Section 3 of this work.

Much of the research carried out on the Ronchi test technique was based on the generation of special grids. General descriptions for obtaining null tests, that is, special Ronchi rulings with studied fringe curvatures which yield straight fringes on the observation plane for particular wavefronts have been reported [Cordero 1990], and optimization of the wavefront measurements through square grids has also been proposed [Cordero 1998]. Phase-shifting configurations for high frequency Ronchi rulings have been shown to have 16 times the dynamic range of a Fizeau interferometer, with phase measurement accuracies of 1/700 [Hibino 1997]. This sort of ruling gives rise to intensity patterns which may be interpreted through phase reduction algorithms designed for interferometric testing of large optics [Wan 1990].

The Ronchi test technique has not been widely implemented as a commercial setup. To our knowledge, only Ann Arbor Optical Company© marketed a Model C Optical Tester© consisting of an optical bench with a set of rulings for the qualitative inspection of optical systems. However, many laboratory applications have been reported. Quantitative studies of spherical aberration in intraocular lenses show that the Ronchi test is a very well-suited technique for such elements [Carretero 1993]. Using high frequency gratings, it has been used in the study of microcapilarity flow under low gravity conditions, by mapping the deformation of a free oil surface [Meyers 1992]. Data treatment techniques for the separation of shadow patterns where data from two orthogonal positions of the Ronchi ruling were simultaneously recorded have also been reported [Stultz 1994].

The present work will focus in following Sections in the development of theoretical and experimental outlines in order to perform high quality topographic measurements using the classical Ronchi test deflectometry technique. Our approach will significatively enhance the results of classical setups through the use of CCD arrays, laser sources, encoder motors and numerical computing power.