A Scanning Phase-Knife Technique for Quantitative Surface Slope Measurements and Defect Identification

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1. Introduction

One of the earliest techniques for evaluating the quality of an optical surface is the Focault knife-edge test, a qualitative means to map the local slope of an optical surface along a particular axis[1]. A Focault knife-edge involves projecting a point source onto or through an optic, translating a one dimensional opaque edge across a returning convergent ray bundle that expands past focus and is imaged onto a detector array or film plane. Light ray bundles obscured by the translation of the knife edge exhibit a smooth change in intensity from maximum light levels to minimum light levels across the optic pupil as a function of local surface slope. The smooth decrease is controlled by the diffraction of light, depending on the aperture and the test wavelength. More recently, the advent of digital imaging arrays has allowed the extension of this technique to quantify the specific surface slope of an optic or optical system[2,3]. In the digital versions of the Focault test, the 50 percent decrease point in the illumination curve was selected to denote surfaces with the transverse slope deviation that match the position of the knife-edge. Limitations in the classic Focault test arise from the point source, which is usually an extended source larger than the diffraction limit of the collimator or optic and the use of an asymmetric signal such as the falling intensity edge to denote the transverse ray aberrations. The advantage of slope measurement systems is that they directly measure surface slope and are less sensitive to changes in the overall path length and vibration than an interferometer. Disadvantages include the requirement of calibration and numerical integration of the slope measurement to calculate the surface profile. Recent work concerning numerically integrated surface slopes has been found to closely match results obtained with an interferometer in previous work on the classic knife-edge[3]. Investigation of alternate wavefront measurement techniques as applied to Inertial Confinement Fusion laser mirror assemblies prompted revisiting this concept with two improvements: a ‘quasi-perfect’ spherical point source from a single-mode fiber and a switch to a half-wave phase-knife to provide a symmetric fringe function for improved signal processing. The encouraging results from this concept found even greater relevance in the inspection of magnetic media substrates or platters.

2. Application

Magnetic media platters are precision, polished disks produced at a rate measured in the tens of millions per month. The magnetic platters used in the highest density disk drives manufactured today require extremely flat and smooth surfaces for the air-bearing read/write heads to fly at the proper uniform height to maintain data integrity. In the last two years, the flying heights of these heads have dropped from above 1 microinch down to a current height of 0.7 microinches (18 nm). The crucial height requirement is the head distance above the sputtered magnetic layer, which has an additional overcoat layer of diamond-like carbon 8 nm thick. This leaves a total flying height spacing of 26 nm above the magnetic layer that must be maintained to within ± 6 nm for reliable data storage/retrieval. The integral air-bearing built into the read/write head surface allows the head to follow the surface for moderate departures from flatness. No longer is absolute flatness of the disk as critical, but instead both the tangential curvature and radial curvature have close tolerances; curvature measurement being well suited for the scanning phase knife.

The most commonly used substrate is a high tensile strength aluminum alloy that is polished and then nickel plated prior to sputtering the magnetic layer. The flatness of the media substrate is controlled in the polishing of the aluminum disk on large double-sided polishing tools that polish many parts in parallel. A common defect that now prevents certain substrates from being utilized at these high storage densities is the substrate polishing process. Small nodules of different alloy phases are present in the aluminum substrate, and this material polishes at a slightly differential rate from the bulk material. This differential removal rate results in the creation of small diameter (grain size < 1 mm), very shallow pits ranging from 3 to 12 nm deep. These pits are only a few hundred microns across and the air-bearing head will not track over any defect smaller than 1 mm while maintaining proper height. The read/write signal drops below threshold where the head glides over the small diameter pits. Defects deep enough to cause a problem (> 5 nm) cannot be easily seen on commercial interferometers that are marketed to this industry. These pits are at the extreme limits of height resolution for the interferometers and the pit diameters are at the spatial resolution limit of these systems. However, the small diameters of the critical defect pits are such that the slope of the pit surface has a mean distribution of 10 to 20 microradians, well within reasonable detection by digital slope measurement. There is a need in this industry to simultaneously measure the disk curvatures that determine head tracking performance as well as identify defects that disqualify platter substrates. Currently, because of the sensitivity, vendors use old schlieren systems to inspect for these defects in a qualitative evaluation in place of an interferometer.

3. System Concept

The optical layout of the system is shown in Figure 1. The point source used for this prototype is a single mode fiber coupled to a 635 nm laser diode with an exit aperture of 3.5 microns from the fiber, well below the diffraction limit of the collimation lens. The diffraction of the light from this small aperture will theoretically describe almost a perfect spherical wave (within half a nanometer), and this has been shown by phase shifting interferometry[4]. The numerical aperture of the spherical light exiting the fiber overfills the 100 mm input aperture of the 780 mm focal length lens, providing uniform illumination of the media platter. The light expanding from the fiber passes through a 50 percent reflecting nitrocellulose pellicle oriented at 45 degrees prior to reaching the aplanatic doublet lens and disk. After reflecting from the 95 mm diameter disk surface, the return beam reflects off the pellicle and is transmitted through a phase knife at the conjugate focal plane. The phase knife is designed with two orthogonal edges, each at 45 degrees to the direction of travel to allow both X and Y axis cuts with a single translation stage. After the beam expands beyond the phase knife, the disk surface is relay imaged by a lens onto a Sony CCD camera array and digitized for each phase knife position. The phase knife is translated at the Fourier plane of the disk image and transverse ray aberrations calculated from the position of the symmetric signal peak in the same manner as described in reference 2 and 3. No vibration isolation or thermal control was used on the system.

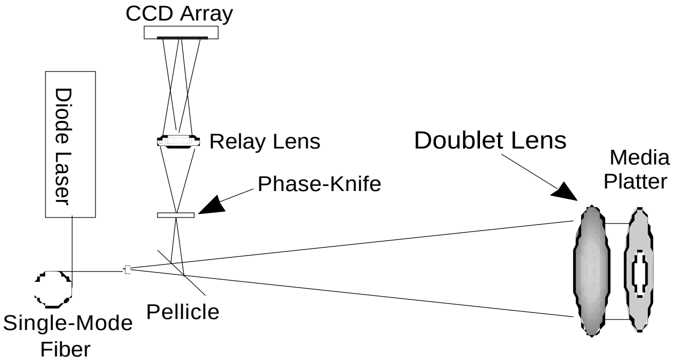


Fig. 1 - Phase Knife Optical Layout

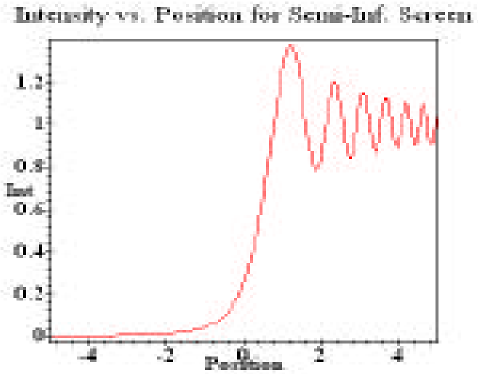
4. Theory

The point source provided by the single-mode fiber expands to fill a 100 mm aperture of an aplanatic doublet to create a collimated wavefront at 635 nm. The plane wavefront then reflects from the surface of the media platter with twice the surface slope errors and is back collimated through the doublet to a conjugate point source in the plane of the half-wave phase step for λ = 635 nm. The interaction of the half-wave phase step with the surface slope of the disk is a simple convolution in the Fourier plane that is governed by diffraction theory. The distance of the conjugate image formed from the phase-knife and the numerical apertures involved allow for the quadratic Fresnel diffraction approximation to be used. A traditional knife edge yields an intensity decrease as a function of knife-edge position in the classic Fresnel edge diffraction equation. Prior digital knife-edge instruments selected the 50% intensity reduction point as the transverse ray aberration threshold where the relative position of the knife-edge for each point in the pupil provided a map of the corresponding slope of the surface[3].

For this prototype system, the knife-edge is replaced by a phase-knife that is mathematically represented as a coherent superposition of two Fresnel edge diffraction functions in reverse directions with a phase shift of 180 degrees between the two patterns[5]. The resulting intensity pattern is the magnitude of these two Fresnel functions and the interference at the phase step creates a symmetric oscillatory function with a central ‘dark’ fringe. Figure 2a and Figure 2b compare intensity patterns for both the classic opaque-knife edge and the phase-knife with the central null fringe. The intensity pattern for the phase-knife function is represented below in terms of the Fresnel sine and cosine integrals' as[6]**:**

$$I(\xi) = I_O\left\{\left[C(\beta\xi) - C(-\beta\xi)\right]^2 + \left[S(\beta x) - S(-\beta\xi)\right]^2\right\} \quad \beta = \frac{\pi D}{\lambda f} \quad S(x) = \int_0^x \sin\frac{\pi}{2}t^2 dt \quad C(x) = \int_0^x \cos\frac{\pi}{2}t^2 dt$$

with D the system aperture (100 mm) and f the doublet lens focal length. The phase-knife intensity pattern is quite similar to an enveloped cosine function similar to a ‘coherence envelope’ with the difference that slope is measured instead of OPD. The symmetric central null ‘dark’ fringe provides a negative peak whose exact center is determined using a least-likelihood estimator algorithm. For a 100:1 signal-to-noise obtained on the camera array, the 1-sigma tolerance of the peak locations is approximately 1/250th the full width half maximum (FWHM) of the null fringe. Calculating the aperture diameter and wavelength into the Fourier plane the FWHM of the dark fringe angular width is approximated as an airy disk around 6 microradians wide. The tolerance in determining the peak of this fringe is about 1/250th this value and in practice is limited by the thermal turbulence of the air and vibration.



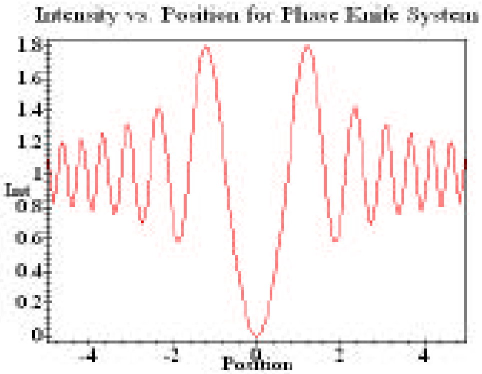


Figure 2a: Image plane intensity from diffraction from an opaque knife edge
Figure 2b: Image plane intensity from diffraction replacing opaque knife edge with 180° retardance phase knife

5. Experimental Results

Figure 3 is a measurement of an aberrated, reflective optic that possessed 0.3 waves P-V (0.078 waves RMS) of astigmatism to demonstrate the slope resolution of the instrument. The phase knife was scanned for a total excursion of 12 microns and the null fringe data converted to surface slope. This small change in flatness is quite evident in the graph and matches the slope data measurements by a Zygo Mark IV. The fine resolution of the slope data plotted at a contour interval of 50 nanoradians shows minimal noise. A repeatability measurement is also included to demonstrate the slope noise floor of the instrument with a λ/20 flat placed into the sample plane. Figures 4 and 5 show two empty cavity data sets taken at separate slope resolutions; the first plotted at 10 nanoradians per contour and the second at 5 nanoradians per contour line. A small amount of coma is visible in the slope data image indicating that the alignment of the lens axis to the fiber is not optimized for the flattest instrument background slope. In use, a flat is used to calibrate this background slope for later subtraction.

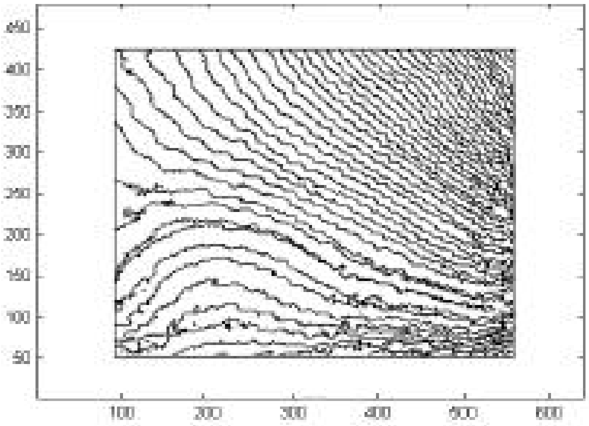


Figure 3 - Slope Data of Astigmatic Optic (Contour interval ~ 50 nanoradians)

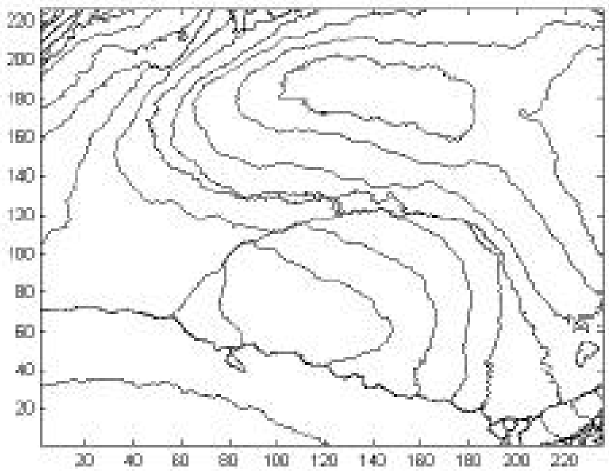


Figure 4 - First empty cavity data set
(Contour interval ~ 10 nanoradians)

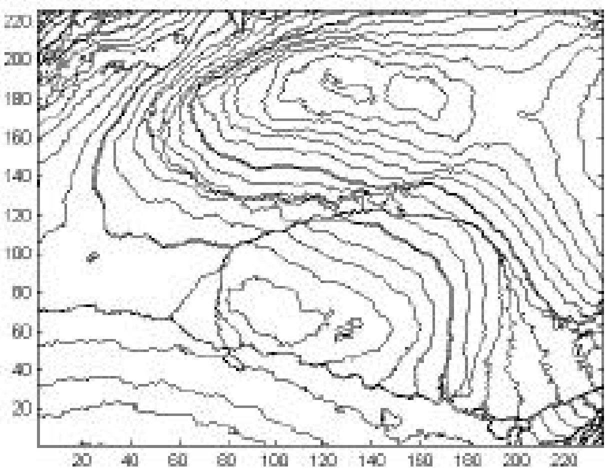


Figure 5 - Second empty cavity data set
(Contour interval ~ 5 nanoradians)

6. Conclusions

A prototype scanning phase knife measures surface slope of deformed optics or magnetic media substrates by digitally analyzing the recorded image of a surface as a 180 degree retardance phase step is scanned across the Fourier plane of the surface image. The high sensitivity of the scanning phase knife to local surface slope identified extremely shallow pits of limited extent not normally visible in an interferometer. The instrument is ideally suited for critical disk curvature metrology for head tracking performance along with determining overall surface flatness. The phase-knife slope measurement technique is less sensitive to environmental vibration and thermal issues than interferometry and can also identify detects not detected with conventional phase shifting interferometry. Additional data will be presented showing measurements of magnetic media disk flatness and defects along with a discussion of specific slope measurement applications.

7. References

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