Anisotropic scaling of hard disk surface structures

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We present a detailed study of the surface roughness of a computer hard disk using atomic force microscopy and light scattering. The power spectrum density analysis showed that the surface possesses an anisotropic scaling behavior and has both random roughness and periodic roughness components. Quantitative anisotropic correlation length ($\xi$) and roughness exponent ($\alpha$) for the directions parallel and perpendicular to the grooves are obtained. A novel in-plane (measurement parallel to the sample surface) light scattering technique is shown to be particularly useful for the analysis of the rough surface parallel to the grooves. © 2000 American Institute of Physics.

I. INTRODUCTION

Many processes in nature or in manufacturing can generate random rough surfaces. Very often these surfaces can be characterized as being self-affine fractals.\textsuperscript{1,2} They are defined through the surface height–height correlation function $H(r)=\langle[z(r)−z(0)]^2\rangle$, where $z(r)$ is the height of the surface at the position $r(x,y)$ on the surface. For isotropic self-affine surfaces, for which the characteristics of the roughness do not depend on the direction, $H(r)\sim r^{2\alpha}$ for $r\ll\xi$, and $H(r)=\text{constant}$ for $r\gg\xi$. The $\xi$ is the lateral correlation length within which the surface heights of any two points are correlated. The $\alpha$ is called the roughness exponent which lies between 0 and 1 and describes how wiggly the surface is. The isotropic model has been studied quite extensively in recent years. However, in practice there are many surfaces that may not be isotropic, depending on how they are generated. These surfaces can be described by anisotropic scaling theories.\textsuperscript{3–5} Thus far, very few quantitative studies of anisotropic scaling surfaces have been reported.\textsuperscript{5}

In this article, we report a detailed quantitative study of anisotropic scaling characteristics of the surface of a computer hard disk. The reliability and durability of hard disks are determined by a series of tribological factors, among which the surface roughness of the disk plays an essential role.\textsuperscript{6–9} During the read/write operation, the magnetic head initially is in contact with the computer disk. If the disk surface is too smooth, the head will stick onto the disk surface, which inhibits the start-up, and possibly causes permanent damage to the slider/disk. In order to reduce the potential damage, a surface texture is introduced, which breaks the large contact area into many small ones. Although the unit area pressure increases after the introduction of a texture, the net starting torque is reduced. Previous study shows that the actual morphology of the texture is very important to the performance of the hard disk.\textsuperscript{5–9}

Different techniques can be used to characterize the roughness and texture of the hard disk surface. One direct way of probing a disk surface quantitatively is to measure the surface morphology using real-space imaging techniques, such as atomic force microscopy (AFM) and scanning tunneling microscopy (STM). However, light scattering has the advantages that it is nondestructive, and can sample a large surface area. With a proper design, it can be used as a real time monitoring tool. Recently, Stover have used the total integrated scattering (TIS) technique to map the roughness of an entire hard disk.\textsuperscript{10} The TIS technique only provides the vertical roughness parameter, i.e., the root-mean-square (rms) roughness, of the surface. The information on the lateral scale is not available from TIS. In this article, we present a study of diffraction from a hard disk surface with a circumferential texture using both the in-plane and out-of-plane light scattering geometries. From an angular scattering profile, we can obtain the lateral correlation length and roughness exponent in addition to the rms roughness value. We then compare the results with that obtained from the AFM measurements.

II. ANISOTROPIC ROUGH SURFACES AND EXPERIMENTAL TECHNIQUES

The power spectrum density function (PSD) $\text{PSD}(k_x,k_z)$ and height–height correlation function $H(r)$ are two useful functions to characterize a random rough surface. PSD($k_x,k_z$), which reflects the spatial frequency variation of the surface in the reciprocal space, is defined as
where \( k_x \) and \( k_y \) are the surface spatial frequencies, \( A \) is the area of the scatterer, and \( z(x,y) \) is the surface height function. \( H(\mathbf{r}) \) on the other hand is a real-space function and is defined as

\[
H(\mathbf{r}) = \left( (z(\mathbf{r} + \mathbf{p}) - z(\mathbf{p}))^2 \right).
\]

The averaging in this function is carried out through the surface position vector \( \mathbf{p} \). Zhao et al. showed that for an anisotropic random rough surface Eqs. (1) and (2) can have the following forms: \(^{11}\)

\[
\text{PSD}(k_x, k_y) = \frac{1}{A} \left| \frac{1}{2\pi} \int z(x,y) e^{i(k_x x + k_y y)} dx dy \right|^2,
\]

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\[
\text{PSD}(k_x, k_y) = \frac{2 \xi_x \xi_y w^2 \Gamma(\frac{1}{2} + \alpha_x) \Gamma(\frac{1}{2} + \alpha_y)}{\Gamma(\alpha_x) \Gamma(\alpha_y)} \times (1 + k_x^2 \xi_x^2)^{-1/2 - \alpha_x} (1 + k_y^2 \xi_y^2)^{-1/2 - \alpha_y},
\]

\[
H(\mathbf{r}) = 2w^2 \left[ 1 - \frac{4}{\Gamma(\alpha_x) \Gamma(\alpha_y)} \xi_x^2 \xi_y^2 \frac{\xi_x x \alpha_x}{2} \frac{\xi_y y \alpha_y}{2} \right]
\]

\[
\times K_{\alpha_x} \left( \frac{x}{\xi_x} \right) K_{\alpha_y} \left( \frac{y}{\xi_y} \right),
\]

where \( w \) is the rms roughness of the surface heights, \( \xi_x \) and \( \xi_y \) are the correlation lengths in the \( x \) and \( y \) directions, respectively. Similarly, \( \alpha_x \) and \( \alpha_y \) are the roughness exponents in the \( x \) and \( y \) directions, respectively, and reveal the scaling anisotropy of the surface. The function \( \Gamma(x) \) in the above equations is the Gamma function and \( K_{\alpha}(x) \) represents the modified Bessel function of the \( \alpha \)th order. Equation (3) has the property that PSD \( \propto k_x^{-1 - 2\alpha_x} \) (or PSD \( \propto k_y^{-1 - 2\alpha_y} \)) when \( k_x \) (or \( k_y \)) is much larger than \( \xi_x^{-1} \) (or \( \xi_y^{-1} \)) while \( k_y \) (or \( k_x \)) remains constant.

Light scattering can provide the surface PSD directly. Similar to the position vector in the real space, the light scattering traces the reciprocal space with the momentum transfer vector \( \mathbf{k} \). The momentum transfer vector components can be expressed along the perpendicular and parallel directions (\( x \) and \( y \)) to sample surface as\(^{12,13}\)

\[
k_x = k \cos \theta_i + \cos \theta_s,
\]

\[
k_y = k \sin \theta_i \cos \phi - \sin \theta_s, \quad \text{and}
\]

\[
k_y = k \sin \theta_s \sin \phi_s.
\]

The surface is assumed to be in the plane formed by the \( x \) and \( y \) axes, and \( k = 2\pi/\lambda \) representing the wave number of the incident light with wavelength \( \lambda \), where \( \theta_i \) is the angle of incidence and the detector is positioned at the polar angle \( \theta_s \) and azimuthal angle \( \phi_s \). The momentum transfers \( k_x \) and \( k_y \) defined in Eqs. (6) and (7) give the surface spatial frequencies \( k_x \) and \( k_y \) used in Eqs. (1) and (3).

For the case of light scattering from surfaces in the small roughness regime, i.e., \( (4\pi w \cos \theta_i/\lambda)^2 \ll 1 \), the PSD can be obtained from the measured scattered light intensity\(^{10}\)

\[
\text{PSD}(k_x, k_y) = \frac{C}{Q \cos^2 \theta_i \cos \theta_s I}.
\]

The \( I = I(\theta_i, \theta_s, \phi_s) \) is the diffuse part of the measured intensity. The \( Q = Q(\theta_i, \theta_s, \phi_s, \epsilon) \) is a polarization dependent
factor, where $\varepsilon$ is the sample dielectric constant. The $C = \varepsilon^\nu/(16\pi^2\Omega_i\lambda)$ is a constant in our light scattering experiments. Here, $\Omega_i$ is the solid angle of the detector and $\lambda$ is the incident light intensity. The $k_x$ and $k_y$ are calculated from Eqs. (6) and (7).

III. EXPERIMENTAL RESULTS

A. AFM measurements

AFM scans were performed using a Park Scientific Instruments AutoProbe CP with Si$_3$N$_4$ tips. The typical radius and the tip side angle were about 10 nm and 10°, respectively. The scan sizes ranged from 3 to 100 $\mu$m. The measured rms roughness of the hard disk surface was $w$ = 20.0 ± 0.5 nm. A 40 $\mu$m AFM image is shown in Fig. 1(a). The PSD can be obtained by taking a discrete Fourier transform of the AFM images. Figure 1(b) shows the top view of the PSD obtained from the 40 $\mu$m AFM image of Fig. 1(a). The spectrum is a thin strip (wall) lying on $k_y$ = 0, which reveals a clear anisotropic behavior of the surface. Note that the width of the wall increases slightly as we go to higher frequencies on $k_x$. This is expected from the PSD of a curved one-dimensional random rough surface. What we cannot see from Fig. 1(b) is the diffraction pattern with a characteristic frequency $k_y$, reflecting a possible periodic structure lying parallel to the $y$ direction. Church et al. argued that, due to the curvature of the texture, the peak due to this characteristic frequency would be stretched out perpendicular to the PSD strip and would appear to be a line. When we increase the contrast of Fig. 1(b), by chopping off the high intensity part and rescaling the contrast of (b), we see a pair of lines parallel to $k_y$ axis on both sides of $k_y$ = 0 that intercept at $k_x$ = $\pm k_y$. We have observed similar lines from other AFM scan sizes. The frequency position $k_y$ = 10.1 ± 0.5 $\mu$m$^{-1}$ of this line corresponds to the spatial wavelength of $\sim$0.62 ± 0.03 $\mu$m, which is the approximate groove separation ($\xi_{grv}$) on the hard disk. Notice that there is a dark line along the $k_y$ axis around $k_x$ = 0 in Fig. 1(b). This dark line is actually due to an artifact, which is induced by the drift of the piezoscanner during the scanning along the $x$ direction and image correction. This artifact causes unreliable PSD values around that low frequency regime.

From the AFMs PSD and height–height correlation results for the 100 $\mu$m scan size, we calculated $\alpha_x$, $\xi_x$ (perpendicular to the grooves) and $\alpha_y$, $\xi_y$ (parallel to the grooves) using Eqs. (3) and (4). These values are listed in Tables I and II and are consistent with those obtained from the 70 $\mu$m scans. Figure 2 shows the fit of the PSD line scan located at $k_y$ = 0 with Eq. (3), which gave $\alpha_x$ = 0.54 ± 0.05. The fit of the PSD in this direction could not give a satisfactory $\xi_x$ value due to the artifact in the PSD as we get closer to the dark line region. The height–height correlation function analysis was very dependent on the scan size (sampling window) and did not give consistent $\alpha_x$ and $\xi_x$ values. The analysis parallel to the grooves was much more free from the artifacts. We obtained the average values of $\alpha_x$ = 0.70 ± 0.10 and $\xi_y$ = 9.06 ± 0.21 $\mu$m from the fit of the PSD curves at various constant values of $k_y$ (but not at $k_y$ = 0 where the dark line lies). Note that the width of the PSD wall along $k_y$ is inversely proportional to $\xi_y$. Also the analysis of

<table>
<thead>
<tr>
<th>Method</th>
<th>$\xi_x$ ($\mu$m)</th>
<th>$\alpha_x$</th>
<th>$\xi_{grv}$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out-of-plane light scat. PSD</td>
<td>2.31 ± 0.24</td>
<td>0.45 ± 0.07</td>
<td>0.70 ± 0.02</td>
</tr>
<tr>
<td>AFM-PSD</td>
<td>...</td>
<td>0.54 ± 0.05</td>
<td>0.62 ± 0.03</td>
</tr>
</tbody>
</table>

FIG. 2. A PSD profile perpendicular to the grooves at $k_y$ = 0 from a 100 $\mu$m scan size AFM image. The fit by Eq. (3) is also shown as a solid curve.

FIG. 3. A height–height correlation function $H(y)$ parallel to the grooves obtained from a 70 $\mu$m AFM image. A fit shown as a solid curve to Eq. (4) gives the correlation length and roughness exponent.

TABLE I. The extracted values of the lateral correlation length ($\xi_x$), roughness exponent ($\alpha_x$), and groove separation ($\xi_{grv}$) in the direction perpendicular to grooves.

<table>
<thead>
<tr>
<th>Method</th>
<th>$\xi_x$ ($\mu$m)</th>
<th>$\alpha_x$</th>
<th>$\xi_{grv}$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-plane light scat. PSD</td>
<td>8.61 ± 0.17</td>
<td>0.95 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>AFM-PSD</td>
<td>9.06 ± 0.21</td>
<td>0.70 ± 0.10</td>
<td></td>
</tr>
<tr>
<td>height-height</td>
<td>7.91 ± 0.20</td>
<td>0.80 ± 0.06</td>
<td></td>
</tr>
</tbody>
</table>
\( H(y) \) with Eq. (3) gave \( \alpha = 0.80 \pm 0.06 \) and \( \xi = 7.91 \pm 0.20 \) \( \mu \text{m} \). In Fig. 3 we plotted the \( H(y) \) obtained from a 70 \( \mu \text{m} \) scan size from the AFM measurements.

### B. Light scattering measurements

In the light scattering experiments, we used a He–Ne laser of wavelength \( \lambda = 0.633 \) \( \mu \text{m} \) illuminating an area of approximately \( 5000 \times 5000 \) \( \mu \text{m}^2 \) on the hard disk surface. The details of the setup will be published elsewhere.\(^{12}\) The measurement geometry is shown in Fig. 4. In Fig. 4, \( \varphi_r \) is the sample rotation angle with reference to the position where groove lines are perpendicular to the plane formed by the incident light beam and the surface normal. The out-of-plane measurements were carried out by setting \( \theta_r = 80^\circ \) and \( \phi_r = 0^\circ \). Then we rotated the detector polar angle \( \theta_s \) from \(-90^\circ\) to \(90^\circ\) in a plane perpendicular to the sample surface. On the other hand, for the in-plane scattering geometry, both the incident angle \( \theta_i \) of the laser beam and the polar angle \( \theta_s \) of the detector were fixed at \(47^\circ\) but the azimuthal angle \( \phi_s \) was rotated in a plane parallel to the sample surface from \(-180^\circ\) to \(180^\circ\). The numbers \( 4 \pi w \cos \theta_i / \lambda \) become 0.07 and 0.005 with \( \theta_i = 47^\circ \) and \(80^\circ\), respectively, for the roughness value of \( w = 20.0 \pm 0.5 \) nm. Since these numbers are sufficiently smaller than 1, the surface belongs in the small roughness regime, and the measured light scattering intensity profiles can be converted to the PSD by Eq. (8).

#### 1. Out-of-plane measurements

We aligned the groove lines parallel to the \( y \) axis. Therefore the PSD wall would rest along the \( k_x \) direction in the reciprocal space. We performed the out-of-plane measurements with \( \phi_r = 0^\circ \) (therefore \( k_z = 0 \)). The measured out-of-plane intensity profile was used in Eq. (8) to calculate the PSD\((k_x,0)\) perpendicular to the grooves. We showed the normalized intensity, the corresponding PSD profiles, and the instrument response function (measured from a flat Si sample as a reference) in Fig. 5(a). The large drop of the intensity at high frequencies is due to an artifact from the detector when it is moved to a position, where the finite size detector starts to block the incident light. We subtracted the instrument response from the light scattering intensity profile to get the diffuse part (PSD). We plotted this PSD profile in the log–log scale as shown in Fig. 5(b). Just as the PSD obtained from the 100 \( \mu \text{m} \) scan size AFM image, the out-of-

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**FIG. 4.** A schematic of the light scattering geometry. The sample shown is a periodic surface which can be rotated in-plane by \( \varphi_r \). The azimuthal angle \( \phi_r \) of the detector can be rotated between \(-180^\circ\) to \(180^\circ\) in a plane parallel to the sample surface (in-plane geometry) and also the polar angle \( \theta_s \) can be rotated from \(-90^\circ\) to \(90^\circ\) in a plane perpendicular to the sample surface (out-of-plane geometry).

**FIG. 5.** (a) Normalized out-of-plane light scattering intensity and the corresponding PSD profiles. The instrument response PSD profile is also shown as a dashed curve. (b) One-dimensional PSD profile at \( k_y = 0 \) plotted in the log–log scale. The fit by Eq. (3) is also shown as a solid curve.
plane light scattering PSD at \( k_x = 0 \) does not have an obvious peak on the tail that would belong to a periodic surface component. Using Eq. (3) to fit the light scattering PSD(\( k_x, 0 \)), we obtained the roughness exponent and lateral correlation length perpendicular to grooves to be \( \alpha_x = 0.45 \pm 0.07 \) and \( \xi_x = 2.31 \pm 0.24 \mu m \), respectively.

Considering the possibility of a peak hidden in the random-roughness PSD profile due to a periodic component, we performed a modified out-of-plane light scattering measurement. In this type of geometry, both \( \theta_s \) and \( \phi_s \) were changed in such a way that the detector was rotated in a plane that was perpendicular to the surface but placed at a nonzero \( y \) away from the incident light plane. Using this, we were able to obtain a PSD profile along \( k_y \) at a fixed but nonzero value of \( k_x \). Therefore, the detector passed through the PSD line due to the periodic roughness, which was lying along the \( k_x \) direction. This is similar to the AFM line shape of the PSD component at \( k_x \neq 0 \) shown in Fig. 1(c) as a result of the periodic grooves on the surface. The diffuse part of the PSD as shown in Fig. 6 has a well resolved bump located at \( k_x = 8.98 \mu m^{-1} \), which reflects the periodic roughness of the grooves. The central position of a Gaussian fit to this bump gives an average groove separation of \( s_{grv} = 0.70 \pm 0.02 \mu m \). This result agrees well with the one obtained from the AFM analysis, which is also shown in Fig. 6. Therefore, the light scattering PSD suggests that, the hard disk surface has both a one-dimensional roughness and a periodic roughness.

2. In-plane measurements

When the groove lines were parallel to the \( y \) axis, the PSD wall would lie along the \( k_x \) axis in the reciprocal space. As the sample was rotated around the \( z \) axis with an angle \( \varphi_z \) from this reference position, the PSD wall also rotated around the \( k_z \) axis with the same \( \varphi_z \). In Fig. 7(a), we show the in-plane light scattering intensity results at different sample rotation angles. We see that the in-plane light scattering is very sensitive to the anisotropy of the surface. Whenever the detector intersects with the PSD wall in the reciprocal space, it reads a high intensity value. We showed this situation schematically as the insert in Fig. 7(a). The circle represents the path of the detector. For each rotation, the detector cuts the PSD wall at a different \( k_z \) value, which results in a peak positioned at a different \( \phi_s \). We can show that the peak of the in-plane light scattering intensity profile changes as

\[
|\phi_{s, \text{peak}}| = \pi - 2|\varphi_z|. \tag{9}
\]

Next, we did a modified in-plane measurement, where \( \theta_s \) and \( \phi_s \) were still kept constant but this time they were set not to be equal to each other. The groove lines were placed parallel to the incident beam plane (along the \( x \) axis), where the PSD wall is positioned to be at \( k_y = 0 \) along the \( k_y \) axis. In Fig. 7(b), we show the result of such a measurement. From Eq. (6), the reciprocal space locations of the both peaks in the profile correspond to \( k_z = 0 \), which is consistent with the wall-shaped picture of the PSD. The observed finite peak widths of the profiles is due to the finite correlation length \( \xi_y \). Since the detector cuts almost perpendicularly through the PSD wall (parallel to the grooves in real space), we took...
the local roughness along the grooves is smoother than that
This means the correlation length along the grooves is about
the intensity peak profiles and converted them to the corre-
sponding PSD cross-sections along the \( k_x \) axis at constant
Figure 8 shows a representative PSD obtained in this way. The PSD analysis of these peaks gave the average cor-
relation length and roughness exponent to be \( \xi_y = 8.61 \pm 0.17 \mu m \) and \( \alpha_y = 0.95 \pm 0.03 \), respectively. In Fig. 8, we also compare the in-plane light scattering PSD data with the
PSD line scan obtained from the AFM at the same \( k_y \) value.

**IV. CONCLUSIONS**

In conclusion, we conducted a detailed measurement of the surface roughness of a hard disk along directions parallel and perpendicular to the grooves using AFM and light scattering. The power spectrum density function was used throughout our analysis. Tables I and II summarize the correlation lengths \( \xi_x \) and \( \xi_y \) and roughness exponents \( \alpha_x \) and \( \alpha_y \) obtained from the light scattering and AFM analysis. These parameters clearly show the anisotropic roughness behavior on the hard disk surface with \( \xi_y > \xi_x \) and \( \alpha_y > \alpha_x \). This means the correlation length along the grooves is about three times larger than that perpendicular to the grooves and the local roughness along the grooves is smoother than that

perpendicular to the grooves, as expected. Table I also shows the measured average groove separation (\( s_{grv} \)), which re-
veals the periodic roughness component on the surface. It is
seen from Table I that the results of the out-of-plane light scattering and AFM agree well except for \( \xi_y \). The AFM analysis could not provide a reliable \( \xi_y \) value due to an AFM artifact generated at low frequencies. In contrast, the out-of-plane light scattering can give reliable roughness parameters without the same artifact. For the analysis along the direction parallel to the grooves shown in Table II, both the in-plane light scattering and AFM analysis give consistent results. In general this novel in-plane light scattering technique can be used to obtain intensity profiles that can provide quantitative information on the surface roughness along the direction parallel to the grooves.

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