

-1-

Title of the Invention

LOW FRICTION NON-GAUSSIAN SURFACE AND METHOD OF DETERMINATION OF OPTIMUM LOW FRICTION SURFACE PARAMETERS

Field of the Invention

The present invention pertains generally to tribology and microtribology and specifically to tribology of low friction surfaces.

Background of the Invention

Tribology, the study of contacting solid surfaces in relative motion, is applicable to every mechanical device and operation. Examples of productive wear are writing with a pencil, machining, and polishing. Examples of productive friction are brakes, clutches, driving wheels on trains and automobiles, bolts and nuts. Examples of unproductive friction and wear are internal combustion and aircraft engines, gears, cams, bearings and seals. According to some estimates, losses resulting from ignorance of tribology amount to roughly 6% of the U.S. gross national product, and approximately one-third of the world's energy resources in present use represent friction in one form or another. The science of tribology therefore seeks to minimize and eliminate losses resulting from friction and wear at all levels of technology involving moving contacting surfaces.

Magnetic recording is one area of modern technology which suffers from unproductive friction and wear. Magnetic recording is extensively used in audio, video, and digital applications in the form of tapes and disks. The industry is expected to grow by a factor of five or more in the next decade. This growth will be accompanied by dramatic improvements in the technology, and the potential exists for magnetic-recording densities to improve by at least one order of magnitude. Magnetic-recording is accomplished by relative motion between a magnetic head and a magnetic medium. Types of magnetic media for digital recording are: flexible media (tapes and floppy disks) and rigid disks. Physical contact between head and medium occurs during starts and stops and hydrodynamic air films develop at high speeds. Flying heights (mean separation between head and medium) are on the order of 0.1 micrometer comparable to surface roughness of the mating members. The need for higher and higher recording densities requires that media surfaces be as smooth as possible and flying heights be as

low as possible. Smoother surfaces lead to increased static and kinetic friction and wear. In the case of heads used in conjunction with rigid disks, the dynamics of a head are very critical in maintaining head-disk separation. All magnetic media have to be lubricated sufficiently to minimize head and magnetic-medium wear. The lubrication is carried out either topically or in bulk. Disk/head interface tribology is the limiting factor in achieving maximum data storage density.

High magnetic storage density in modern disk drives is achieved by the use of very smooth thin-film rigid disks that allow ultra-low flying of read/write head sliders over the disk surface. However, smooth surfaces result in stiction (high static friction) during rest and high stiction/friction during the contact start/stop (CSS) operation, especially with the presence of a thin film of liquid lubricant or adsorbed water vapor at the head-disk interface. Disk surfaces are therefore textured to minimize stiction/friction. There is a critical h/σ (total liquid film thickness/standard deviation of surface heights) above which stiction increases rapidly with an increase in the liquid film thickness. Distribution of local roughness plays an important role in friction/stiction and wear. Thus optimization of roughness distribution on the disk surface is required. In most models, surface height distribution is assumed to follow a gaussian distribution. However, engineering surfaces are frequently non-gaussian with the degree of non-gaussian characteristics dependent upon materials and surface finishing processes used. For example, magnetic rigid disk surfaces used in the magnetic storage industry are highly non-gaussian. The use of a gaussian analysis in such cases can lead to erroneous results.

Contact of two rough surfaces at an interface occurs at a small fraction of the nominal area of contact. Real area of contact and interfacial adhesion primarily control the friction of an interface. With the presence of a thin film of liquid lubricant or adsorbed water layer at the interface, menisci form around the contacting and near-contacting asperities. The meniscus formation results in stiction problems in the head-medium interfaces. Stiction in rigid disk drives is intimately related to the ratio of the liquid film thickness (h) and the composite standard deviation of the surface heights of disk and head surfaces (σ). For the same liquid film thickness, rougher disks (having a higher σ) exhibit a lower stiction than smoother disks (Bhushan, 1990). Normally in disk drives, the stiction induced with meniscus bridges is a more serious problem than the kinetic friction during sliding. CSS operations result in wear of surface making surfaces smoother which increases stiction after use. There is a need therefore for a magnetic media surface which has optimum roughness

-3-

which minimizes friction and stiction to reduce wear and prolong the life of the recording media.

Based on classical theory of friction (Bowden and Tabor, 1950) the kinetic friction is proportional to the real area of contact which is high for smoother surfaces (Greenwood and Williamson, 1966). For partially wet contacts, menisci bridges are formed at the interface which result in intrinsic attractive (meniscus) force leading to high static friction. The number of bridges and asperities increase for smoother surfaces leading to high static friction. Thus minimum kinetic and static friction occurs for two rough surfaces, viz. a rough slider against a rough disk. This however does not satisfy the objective of achieving a high recording density, which is obtained by the use of smooth surfaces for the head and the disk. Thus optimization of the roughness distribution of head and disk surfaces is required in order to satisfy both objectives. Optimization of surface roughness also reduces wear.

Summary of the Present Invention

The present invention provides a low friction surface and method of design which minimizes static and kinetic friction and resultant wear of parts in moving contact. In one embodiment, the present invention provides a magnetic media storage device having a non-gaussian surface with a roughness distribution which minimizes static and kinetic friction by having positive skewness and high kurtosis values. In accordance with one aspect of the invention, a magnetic media storage device has a low friction surface with a positive skewness value and a kurtosis value of 3 or greater. In accordance with another aspect of the invention, a magnetic media storage device has a low friction surface with a skewness value in the approximate range of 0.0 to 0.2 and a kurtosis value in the approximate range of 3 to 10 or higher. These surfaces will also result in low wear.

The invention further provides a method of determining an optimum non-gaussian surface for a magnetic media storage device which minimizes static and kinetic friction and wear by using models of real area of contact, number of contacts, contact pressure and meniscus force at wet interfaces in probability density functions or computer generated surfaces with different skewness and kurtosis values. From curves generated by the probability density functions or computer generated surfaces, optimum values of skewness and kurtosis are determined for minimum static and kinetic friction. By the method of the invention it is determined that a magnetic media storage device surface with a positive skewness value and a kurtosis value of at least 3 or greater substantially lowers the real area of contact, meniscus force, and sensitivity of film thickness to static friction between the

magnetic media storage device and a slider head to thereby reduce friction and wear of the storage device.

Although the invention is described with reference to a computer hard disk and the disk/head interface as an example of types of surfaces which benefit from the low-friction and wear attributes of the invention, it is understood that the principles of the invention are applicable to all materials used for any machine component which is in moving (i.e., sliding or rolling) contact with another material such as, for example and without limitation, engine pistons, gears, bearings, seals, etc.

These and other aspects of the invention are herein described in particularized detail with reference to the accompanying Appendix, Tables and Figures.

Description of the Figures

In the accompanying Figures:

FIG. 1 schematically illustrates surfaces with various skewness and kurtosis values;

FIG. 2 graphically illustrates probability density functions for surfaces with different skewness and kurtosis values;

FIG. 3 graphically illustrates the effect of skewness on normalized mean separation, normalized number of contacts, normalized real area of contact, normalized mean asperity contact area and normalized mean contact pressure as a function of normalized load ($K=3$);

FIG. 4 graphically illustrates the effect of kurtosis on normalized mean separation, normalized number of contacts, normalized real area of contact, normalized mean contact asperity area and normalized mean contact pressure as a function of normalized load ($Sk=0$);

FIG. 5 graphically illustrates the effect of skewness and kurtosis on the fractional real area of contact and relative meniscus force at applied pressures of 32.8 kPa and 328 kPa ($E'=100\text{GPa}$, $\eta = 500,000/\text{mm}^2$, $A_a=0.915 \text{ mm}^2$, $\sigma_p = 1\text{nm}$, $R_p=10\mu\text{m}$);

FIG. 6 graphically illustrates the relative meniscus force as a function of h/σ for different skewness and kurtosis values at an applied pressure of 32.8 kPa ($E' = 100 \text{ GPa}$, $\eta = 500,000/\text{mm}^2$, $A_a = 0.915 \text{ mm}^2$, $\sigma_p = 1 \text{ nm}$, $R_p = 10\mu\text{m}$) and,

FIG. 7 graphically illustrates the interplay of the skewness and kurtosis on the fractional real area of contact and relative meniscus force at an applied pressure of 32.8 kPa ($E' = 100 \text{ GPa}$, $\eta = 500,000/\text{mm}^2$, $A_a = 0.915 \text{ mm}^2$, $\sigma_p = 1 \text{ nm}$, $R_p = 10 \mu\text{m}$).

Detailed Description of Preferred Embodiments and Methods

The invention is a low friction non-gaussian surface with a positive skewness value and a kurtosis value of at least 3 or greater and preferably as high a kurtosis value as is possible to create. The inventor has discovered, using the described methods, that a surface with these physical properties in particular is optimal to reduce static and kinetic friction in contact with another surface and thereby minimize mechanical wear from relative motion. In a preferred method of the invention, probability density functions are used to statistically determine optimum surface parameters for a magnetic storage device. (Kotwal and Bhushan, unpublished). Other methods have been used by the inventor to model or represent surface parameters and resultant characteristics, such as for example by using numerical rough surface contact models and computer generated surface models. (Bhushan and Chilamakuri, unpublished). Such alternative methods of surface analysis can be used in accordance with the method of the invention of determining optimum skewness and kurtosis values which minimize friction. The probability density function for surface height defines the probability of locating a point at a height z and is denoted by $p(z)$. The shape of the probability density function offers useful information on the behavior of the random process. This shape can be described in terms of moments of the function about the means, referred to as central moments represented by:

$$m_n = \int_{-\infty}^{\infty} (z-m)^n p(z) dz$$

(1)

where m is the mean height of z which is generally removed before data processing and is therefore zero. The first moment is equal to zero. The second moment m_2 is the variance σ^2 which is the square of the standard deviation or root-mean-square RMS value for $m=0$. It is a measure of the spread of the distribution and therefore of the data. The third moment m_3 is the skewness, a useful parameter in defining variable with an asymmetric nature. Skewness shows degree of symmetry of the profile as shown in FIG. 1. FIG. 1 represents for example a magnetic storage media, a computer hard disk surface or, equivalently, a surface of any object or any mechanical/electro-mechanical device or machine component which is placed in moving contact (e.g., sliding or rolling) with another surface. For a skewed distribution, the distribution gradually rises to a maximum from zero and then falls at a different rate. The difference between the mean and the mode divided

-6-

by the standard deviation is referred to as skewness. If the mean is on the left hand side of the mode of the distribution, the skewness will be negative with a relatively larger number of peaks than valleys at a certain height. A symmetrical distribution about the mean has zero skewness with equal number of peaks and valleys at a certain height. Typically, m_3 or skewness Sk is normalized as follows:

$$Sk = \frac{1}{\sigma^3} \int_{-\infty}^{\infty} (z-m)^3 p(z) dz$$

(2)

where σ is the standard deviation of $p(z)$.

The fourth moment m_4 is called kurtosis and represents the peakedness (degree of pointedness or bluntness) of the distribution. A surface with low kurtosis (K) has a relatively larger number of peaks than valleys at a certain height as shown in FIG. 2. The kurtosis is normalized with respect to the standard deviation of the distribution as follows:

$$K = \frac{1}{\sigma^4} \int_{-\infty}^{\infty} (z-m)^4 p(z) dz$$

(3)

For a gaussian distribution, the probability density function is given by

$$p(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp[-(z-m)^2/2\sigma^2]$$

(4)

A gaussian distribution has a skewness of zero and a kurtosis of 3. Most of the common machining processes produce skew distributions. (Thomas 1982). Grinding and abrasion produce negatively skewed surfaces (Sayles and Thomas 1976). Positive skewnesses are produced by certain milling and turning operations. Positive kurtosis can be produced upon surfaces by various known processes such as mechanical texturing, including free abrasive slurry and tape texturing, deposition of asperities (e.g., etching by photolithography to create asperities of equal height), laser etching, and layering of materials having differing grain sizes. The use of these and other known

processes, as for example described in "Magnetic Slider/Rigid Disk Substrate materials and Disk Texturing Techniques -- Status and Future Outlook", B. Bhushan, Adv. Info. Storage Syst., Vol. 5, 1993, pp. 175-209 incorporated herein by reference, is contemplated to manufacture the surfaces of the present invention.

The method of the present invention uses a probability density function for a non-gaussian surface asperity distribution in a contact model to determine real area of contact and stiction (high static friction), and to determine an optimum skewness and kurtosis for lowest real area of contact and stiction. An alternative method of the invention uses computer generated surfaces to determine optimum skewness and kurtosis values. In the preferred method of the invention as described herein, a probability density function for a non-gaussian distribution uses curve-fitting techniques including (1) the method of percentile points, (2) method of moments, and (3) method of maximum likelihood. The method of moments is ideally suited to the current study as it uses moments of the probability density function to determine the curve fitting parameters. As the skewness and kurtosis are the third and fourth moments of the probability density function, the curve fitting parameters can be determined in terms of the skewness and the kurtosis. Once the probability density function is determined, a contact model can be developed using the Greenwood and Williamson (1966) approach, incorporated herein by reference.

In this particular method of the invention, it is required that a probability density function be generated for a distribution having a known mean, standard deviation, skewness and kurtosis. The method of moments can be used in such a situation. The Pearson system of frequency curves, based on the method of moments, provides a family of curves which can be used to generate an equation for a distribution for which the first four moments are known (Elderton and Johnson, 1969). Pearson defined a criterion κ , given by

$$\kappa = \frac{Sk^2(K+3)^2}{4(2K-3Sk^2-6)(4K-3Sk^2)}$$

(5)

The value of κ determines a type of the curve. Depending on the value of κ , different equations can be obtained for the probability density functions. A list of the different types of curves, their equations and the range of κ for which they are applicable is shown in Table I. There are three main types of Pearson curves which cover the majority of the cases. These are Types I, IV, and VI. This really

covers the whole field, but in the limiting cases when one type changes into another, we reach simpler forms of transition curves. Analytical expressions have been derived for the curve fitting parameters in terms of the standard deviation, skewness and kurtosis of the distribution, see Appendix A (Elderton and Johnson, 1969). The expressions for the parameters for the different types of curves are presented in Appendix A. Based on these expressions a software program was developed to determine the equation and type of curve for a given set of parameters and details for selected skewness and kurtosis values presented in Table II. The probability density function curves generated by this method for different skewness and kurtosis values are shown in Fig. 2. From Fig. 2, it can be seen that a gaussian surface with zero skewness and kurtosis of 3 has an equal number of peaks and valleys at a certain height. A surface with a high negative skewness has a large number of peaks, whereas a surface with a high positive skewness consists of few peaks. A surface with a low kurtosis has a relatively large number of peaks as compared to that of a surface with a high kurtosis.

Non-gaussian probability density functions obtained in this manner are substituted in the classical Greenwood and Williamson model. In this model, it is assumed that all asperities have the same radius R_p and their heights follow a non-gaussian distribution $p(z)$. This model gives expressions for the real area of contact, the normal load and the number of contact spots in terms of the statistical parameters of the distribution. The probability that a particular asperity has a height between z and $z+dz$ above some reference plane will be $p(z)dz$. The expected number of contact spots are given by

$$n = N \int_d^{\infty} p(z) dz$$

(6)

where d is the separation between mean planes of the two surfaces, $p(z)$ is the probability density function of the equivalent surface and N is the total number of asperities. The total load is given by

$$W = \frac{4}{3} N E' R_p^{0.5} \int_d^{\infty} (z-d)^{3/2} p(z) dz$$

(7)

where W is the total load, E' is the equivalent Young's modulus of elasticity given by

-9-

$$\frac{1}{E'} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

(8)

where E_1 and E_2 are the Young's moduli of elasticity for the two surfaces and ν_1 and ν_2 are the Poisson's ratios of the mating surfaces and R_p is the equivalent radius of the peak asperities given by

$$\frac{1}{R_p} = \frac{1}{R_{p1}} + \frac{1}{R_{p2}}$$

(9)

where R_{p1} and R_{p2} are the mean radii of the peaks on the two surfaces. The real area of contact A_r is given by

$$A_r = \pi N R_p \int_d^{\infty} (z-d) p(z) dz$$

(10)

It is convenient to use standardized variables, and describe heights in terms of the equivalent standard deviation of the peak asperities, σ_p , of the two surfaces given by

$$\sigma_p = (\sigma_{p1}^2 + \sigma_{p2}^2)^{1/2}$$

(11)

The surface density of asperities η , is defined to be

$$\eta = N/A_s$$

(12)

where A_s is the nominal contact area. Then Eqs. (6) (7) and (10) reduce to

-10-

$$n = \eta A_a F_0(h)$$

(13)

$$W = \frac{4}{3} \eta A_a E / R_p^{0.5} \sigma_p^{1.5} F_{1.5}(h)$$

(14)

$$A_r = \pi \eta A_a R_p \sigma_p F_1(h)$$

(15)

where h is the standardized separation given by d/σ and

$$F_n(h) = \int_h^\infty (s-h)^n p^*(s) ds$$

(16)

where $p^*(s)$, the standardized height distribution, is the height distribution scaled to make its standard deviation unity.

In addition to the analysis of the real area of contact, it is necessary to obtain values for the meniscus force for the different p.d.f.'s. A model is proposed by Gao et al. (1995) is used to determine the meniscus force. According to this model, the meniscus force is given by

$$F_m = 2\pi R_p \gamma (1 + \cos\theta) N \int_{d-h}^\infty p(z) dz$$

(17)

where F_m is the meniscus force, γ is the surface tension of the liquid, θ is the contact angle and h is the lubricant film thickness. The interplanar separation of d is determined from

(18)

$$W + F_m = \frac{4}{3} E' R_p^{1/2} N \int_d^{\infty} (z-d)^{3/2} p(z) dz$$

An iterative numeral approach is used to solve Eq. (17) and (18).

Different p.d.f.'s are substituted in these equations, corresponding to different skewness and kurtosis to obtain values for the real area of contact and the meniscus force.

Using the contact model described in the preceding section, curves were plotted showing the variation of the normalized mean separation (d/σ), the normalized number of contacts, the normalized area, the normalized mean asperity contact and normalized mean contact pressure. The normalized load is the term

$$\left(\frac{W}{\eta A_s E' R_p^{0.5} \sigma_p^{1.5}} \right)$$

(19)

which is obtained from Eq. (14); the normalized number of contacts is the term

$$\left(\frac{n}{\eta A_s} \right)$$

(20)

which is obtained from Eq. (13) and the normalized real area of contact is the term

$$\left(\frac{A_r}{\pi \eta A_s R_p \sigma_p} \right)$$

(21)

which is derived from Eq. (15). The normalized mean asperity contact area is the ratio of the normalized real area of contact and the normalized number of contacts. Finally the normalized mean contact pressure is the ratio of the normalized load and the normalized real area of contact.

Curves showing the variation of the just mentioned parameters for probability distribution functions having different skewnesses are shown in Fig. 3. The kurtosis for the probability density functions (henceforth referred to as p.d.f.'s) is 3. From these curves it is observed that the p.d.f.'s with a negative value of skewness exhibit

-12-

the highest real area of contact and the highest number of contacts; the more negative the skewness the higher the value of these contact parameters. At high loads, the p.d.f.'s having a high positive skewness exhibit the minimum real area of contact and the number of contacts. The higher the load, the more pronounced the difference between the various p.d.f.'s. At lower loads (normalized load < 1) the behavior is slightly different. The real area of contact and the normalized load show very little variation for zero and positive value of skewness. Moreover, even if such a variation is present, the scale on the vertical axis is too small to detect it. To obtain trends for the contact parameters at low loads, it is necessary to obtain actual value for a given applied load.

The normalized real area of contact varies linearly with the load at all values of skewness. The slope of the line is higher for negative skewness than for positive skewness. The normalized mean asperity contact area is lower for negative values of skewness than for positive values and increases with an increase in load. This is due to the rapid increase in the normalized number of contacts as compared with the normalized real area of contact for the negative skewness, resulting in a lower average asperity contact area. The mean contact pressure increases with an increase in applied load. However, the increase is negligible as compared with the increase in the load, so that it can be assumed that the mean contact pressure is constant. The mean contact pressure increases with an increase in skewness, being the least for the surface with negative skewness and increasing to a maximum for the surface having the highest positive skewness.

Figure 4 shows the variation of the contact parameters at different kurtosis, with the skewness of the p.d.f.'s being zero. It is seen that the normalized real area of contact and the normalized number of contacts are lower for p.d.f.'s with a higher kurtosis. This behavior is monotonic at all loads. Again, the real area of contact varies linearly with the load, with the p.d.f.'s having a lower kurtosis exhibiting a higher slope for the curve. The normalized average asperity area shows different trends for different kurtosis. For a kurtosis below 5, it increases with an increase in load; it is independent of load at a kurtosis of 5, while for a kurtosis above 5, it decreases with an increase in load. This variation can be deduced by observing that the curve between the normalized number of contacts and the normalized load is convex for a kurtosis below 5, linear at 5, and concave for a kurtosis above 5, which accounts for the contrasting trends exhibited by the normalized average asperity area. The variation of the mean contact pressure follows a similar trend. The mean contact pressure seems to be independent of load to a fairly large extent, for all values of skewness and kurtosis.

-13-

The results in the preceding paragraph are valid provided that the contact is elastic. For the application of the model to a head-disk interface of a magnetic storage device such as computer hard disk, it is necessary to assume values for E' , H , η , σ_p and R_p . We consider a nanoslider (pad area $A_p = 0.915 \text{ mm}^2$) against a supersmooth thin-film disk at a nominal load (W) of 3 g. Typical values of $E' = 100 \text{ GPa}$, $H = 7 \text{ GPa}$, $W/A_p = p_a = 32.8 \text{ kPa}$, $\eta = 500,000/\text{mm}^2$, $\sigma_p = 1 \text{ nm to } 5 \text{ nm}$ and $R_p = 10 \text{ }\mu\text{m}$ are used in the analysis. The plasticity index, ψ , is used to determine whether the contact is elastic. The plasticity index is given by (Greenwood and Williamson, 1966)

$$\psi = \frac{E'}{H} \left(\frac{\sigma_p}{R_p} \right)^{1/2}$$

(22)

A plasticity index below 0.6 indicates an elastic contact. Using the values of the parameters mentioned earlier, the value of ψ is 0.14. Thus, the analysis carried out earlier for elastic contacts is valid.

Figure 5 shows the variation of the fractional real area of contact (real area of contact divided by apparent area of contact) with the skewness and the kurtosis, using the previously mentioned parameters. To study the effect of load, calculations at a normal pressure of 328 kPa are also made. It is seen that the fractional real area is high for a negative skewness and decreases with an increase in skewness up to a positive skewness of 0.3 for $p_a = 32.8 \text{ kPa}$, after which it increases again. So a skewness of 0.3 represents an optimum for the applied pressure of 32.8 kPa. The variation of the real area of contact with the kurtosis is continuous, with the higher values of kurtosis resulting in a lower real area of contact. So the highest possible value of kurtosis should be selected in order to minimize the real area of contact. For the higher pressure of 328 kPa, the trend is similar. The optimum value of the skewness is 0.6 for this pressure. The variation of the real area of contact with the kurtosis is similar to that observed at the lower pressure.

Figure 5 also shows the variation of the relative meniscus force (F_m/W) at the two applied pressures with the skewness and the kurtosis for $h/\sigma = 1$, where h is the total liquid film thickness. The surface tension of the selected perfluoropolyether lubricant, γ , is used is 25 g/cm and the contact angle, θ , is 10 degrees. The trend is more or less similar to the trend exhibited by the real area of contact. The only difference is that the minimum meniscus force occurs at a skewness of 0.5 (in comparison to 0.3 for the real area of contact) at an

applied pressure of 32.8 kPa. For $p_a = 328$ kPa, the optimum value of the skewness is 0.7. The relative meniscus force decreases with an increase in the kurtosis for both the applied pressures. It is thus observed that a small positive skewness and a high kurtosis provide an optimization to the surface in order to obtain a minimum real area of contact and meniscus force.

Figure 6 shows the meniscus force for different values of h/σ . For a gaussian distribution, the critical value of h/σ resulting in a high meniscus force is around half. A higher value implies that a thicker liquid film can be applied to the disk. For a negative skewness, the value is lower, while for a positive value, this value is higher. However, the effect of the positive skewness on the critical h/σ is not as significant as the effect of the kurtosis. With a kurtosis of 20, the critical value is 2.5, which is five times as high as that of a gaussian distribution. Thus, a high kurtosis should be selected in order that a thicker lubricant layer be applied to the disk for minimum wear.

Figure 7 shows the interplay of the skewness and the kurtosis on the real area of contact and the relative meniscus force. It is seen that the real area of contact is minimum at a skewness of 0.3, for a kurtosis of 3. However, as the kurtosis increases to 5, this minimum value occurs at a skewness of 0.5. For higher kurtosis, the minimum is at 0.8. This shows that the optimum value of the skewness shifts to the right along the horizontal axis as the kurtosis increases. The effect of the higher kurtosis is significant as it results in a sharp drop in the real area of contact. However, from Figure 7, it is seen that a change in skewness does not result in a significant change in the real area of contact, especially at higher kurtosis. Figure 7 also shows the variation of the meniscus force with kurtosis for various skewness values. The trends are similar to the ones exhibited by the real area of contact mentioned.

The invention thus provides a magnetic media storage device with an optimal surface for reducing friction and wear and a method of design which uses a head-disk interface contact model in non-gaussian probability functions to identify optimum values of skewness and kurtosis of the surface for different loads and meniscus forces. For a given kurtosis, there is an optimum value of skewness. This optimum value depends on the actual value of the kurtosis. For a kurtosis of 3, the optimum value in skewness resulting in the minimum real area of contact is 0.3, while the optimum skewness value resulting in the minimum relative meniscus force is 0.5. For a higher value of kurtosis, optimum skewness value is 0.6 or greater. For a given skewness, the higher the kurtosis, the lower the value of the contact parameters. The sensitivity of the relative meniscus force to the film

-15-

thickness reduces with an increase in the kurtosis. A positive skewness results in a higher value of the critical film thickness. Therefore, in accordance with the invention it is desirable that a magnetic media storage device have a surface which has a positive skewness and as high a kurtosis as possible.

Appendix A Probability Density Functions for Nongaussian Distribution
Equations for probability density functions for different types of curves (Pearson's type of curves) are presented in Table I. The parameters in the curves for the non gaussian probability density functions are functions of the standard deviation, skewness and the kurtosis. This appendix presents the equations for the parameters of the different types of curves.

First Main Type (Type I)

The equation for the probability density function (p.d.f.) is given by

$$p(z) = y_e (1+z/A_1)^{m_1} (1-z/A_2)^{m_2} \quad (-A_1 < z < A_2) \quad (\text{A.1})$$

$$\text{where } (m_1 + 1)/A_1 = (m_2 + 1)/A_2 \quad (\text{A.2})$$

The values to be calculated in order are

$$A_1 + A_2 = \frac{\sigma}{2} (SK^2(r+2)^2 + 16(r+1))^{1/2} \quad (\text{A.3})$$

where

$$r = \frac{6(K - SK^2 - 1)}{(6 + 3SK^2 - 2K)} \quad (\text{A.4})$$

The m's are given by

$$\frac{1}{2} \left(r - 2 \pm r(r+2) \left(\frac{SK^2}{SK^2(r+2)^2 + 16(r+1)} \right)^{1/2} \right) \quad (\text{A.5})$$

(when Sk is positive, m_2 is the positive root) and

$$y_e = \frac{1}{A_1 + A_2} \frac{(m_1 + 1)^{m_1} (m_2 + 1)^{m_2}}{(m_1 + m_2 + 2)^{m_1 + m_2}} \frac{\Gamma(m_1 + m_2 + 2)}{\Gamma(m_1 + 1) \Gamma(m_2 + 1)}$$

-16-

(A.6)

where

$$\Gamma(p) = \int_0^{\infty} e^{-x} x^{p-1} dx$$

(A.7)

Second Main Type (Type IV)

The equation for the p.d.f. is given by

$$p(z) = y_d [1 + (z/a - v/r)^2]^{-m_e - v \tan^{-1}(z/a - v/r)} \quad (\text{A.8})$$

The values to be calculated in order are

$$m_e = 0.5(r+2) \quad (\text{A.9})$$

where

$$r = \frac{6(K - Sk^2 - 1)}{2K - 3Sk^2 - 6} \quad (\text{A.10})$$

$$v = \frac{-r(r-2)Sk}{(16(r-1) - Sk^2(r-2)^2)^{1/2}} \quad (\text{A.11})$$

$$a = \frac{\sigma}{4} (16(r-1) - Sk^2(r-2)^2)^{1/2} \quad (\text{A.12})$$

and

$$y_0 = \frac{1}{aF(r, v)} \quad (\text{A.13})$$

$$\text{where } F(r, v) = e^{-\frac{v\pi}{2} \int_0^{\pi} \sin^2 \phi e^{v\phi} d\phi} \quad (\text{A.14})$$

Third Main Type (Type VI)

The equation for the p.d.f. is given by

-17-

$$p(z) = y_e (1+z/A_1)^{-q_1} (1+z/A_2)^{q_2} \quad (\text{A.15})$$

The values to be calculated in order are

$$a = \frac{\sigma}{2} (Sk^2(r+2)^2 + 16(r+1))^{1/2} \quad (\text{A.16})$$

where

$$r = \frac{6(K-Sk^2-1)}{6+3Sk^2-2K} \quad (\text{A.17})$$

q_2 and $-q_1$ are positive and negative roots respectively of the following equation

$$\frac{r-2}{2} \pm \frac{r(r+2)}{2} \left(\frac{Sk^2}{Sk^2(r+2)^2 + 16(r+1)} \right)^{1/2} \quad (\text{A.18})$$

A_1 and A_2 are given by

$$A_1 = \frac{a(q_1-1)}{(q_1-1)-(q_2+1)}, \quad A_2 = \frac{a(q_2+1)}{(q_1-1)-(q_2+1)} \quad (\text{A.19})$$

and

$$y_e = \frac{(q_2+1)^{q_2} (q_1-q_2-2)^{q_1-q_2} \Gamma(q_1)}{a(q_1-1)^{q_1} \Gamma(q_1-q_2-1) \Gamma(q_2+1)} \quad (\text{A.20})$$

Normal Curve

The equation $p(z)$ for the p.d.f. is

$$p(z) = y_0 \exp(-z^2/2\sigma^2) \quad (\text{A.21})$$

where

$$y_0 = \frac{1}{\sigma\sqrt{2\pi}} \quad (\text{A.22})$$

Transition Type (Type II)

The equation $p(z)$ for the p.d.f. is

-18-

$$p(z) = y_0 (1 - z^2/a^2)^m \quad (\text{A.23})$$

where

$$m = \frac{5K-9}{2(3-K)} \quad (\text{A.24})$$

$$a^2 = \frac{2\sigma^2 K}{3-K} \quad (\text{A.25})$$

and

$$y_0 = \frac{1}{a\sqrt{\pi}} \frac{\Gamma(m+3/2)}{\Gamma(m)} \quad (\text{A.26})$$

Transition Type (Type VII)The equation $p(z)$ of the curve is

$$p(z) = y_0 (1 + z^2/a^2)^{-m} \quad (\text{A.27})$$

where

$$m = \frac{5K-9}{2(K-3)} \quad (\text{A.28})$$

$$a^2 = \frac{2\sigma^2 K}{K-3} \quad (\text{A.29})$$

and

$$y_0 = \frac{1}{a\sqrt{\pi}} \frac{\Gamma(m)}{\Gamma(m-\frac{1}{2})} \quad (\text{A.30})$$

Table I
Equations for probability density functions
(Elderton and Johnson, 1969)

No. of type usually adopted	Equation with origin at mean	Criterion
MAIN TYPES		
I	$p(z) = y_e (1+z/A_1)^{m_1} (1-z/A_2)^{m_2}$	κ negative
II	$p(z) = y_0 [1 + (z/a - v/z)^2]^{-m_0 - v \tan^{-1}(z/a - v/z)}$	$\kappa > 0$ & $\kappa < 1$
VI	$p(z) = y_e (1+z/A_1)^{(-m_1)} (1+z/A_2)^{m_2}$	$\kappa > 1$
TRANSITION TYPES		
Normal Curve	$p(z) = y_0 \exp(-z^2/2\sigma^2)$	$\kappa = 0$, $Sk = 0$, $K = 3$
II	$p(z) = y_0 (1 - z^2/a^2)^m$	$\kappa = 0$, $Sk = 0$, $K < 3$
VII	$p(z) = y_0 (1 + z^2/a^2)^{-m}$	$\kappa = 0$, $Sk = 0$, $K > 3$

Equations for curve fitting parameters are presented in Appendix A

Table II
Probability density functions for surfaces with
various skewness and kurtosis
values based on the Pearson's system of frequency curves

Non Gaussian Parameters		κ	Number of type	Probability density function, $p(z^*)$
Sk	K			
-0.8	3	-0.298	I	$p(z^*) = 0.33(1+z^*/3.86)^{2.14}(1-z^*/1.36)^{2.11}$ $p(z^*) = 0.38(1+z^*/6.36)^{2.21}(1-z^*/2.36)^{2.79}$ $p(z^*) = 0.39(1+z^*/10.72)^{29.80}(1-z^*/4.05)^{10.64}$ $p(z^*) = 0.3989\exp(-0.5(z^*)^2)$ $p(z^*) = 0.39(1+z^*/4.05)^{10.64}(1-z^*/10.72)^{29.80}$ $p(z^*) = 0.38(1+z^*/2.36)^{2.79}(1-z^*/6.36)^{2.21}$ $p(z^*) = 0.33(1+z^*/1.36)^{2.11}(1-z^*/3.86)^{2.14}$
-0.5	3	-0.267	I	
-0.3	3	-0.255	I	
0.0	3	0.000	Normal	
0.3	3	-0.255	I	
0.5	3	-0.267	I	
0.8	3	-0.297	I	
0.0	2	0.000	II	$p(z^*) = 0.32(1-(z^*)^2/16)^{0.5}$ $p(z^*) = 0.3989\exp(-0.5(z^*)^2)$ $p(z^*) = 0.46(1+(z^*)^2/25)^{-4}$ $p(z^*) = 0.49(1+(z^*)^2/8.20)^{-2.92}$ $p(z^*) = 0.51(1+(z^*)^2/5.52)^{-2.68}$
0.0	3	0.000	Normal	
0.0	5	0.000	VII	
0.0	10	0.000	VII	
0.0	20	0.000	VII	

$z^* = z/\sigma$



We claim:

1. A magnetic storage media having a non-gaussian surface with a peak height standard deviation in a range of 1nm to 5nm, the surface comprising a positive skewness value determined as a third moment of a probability density function of the surface and a kurtosis value of 3 or greater, determined as a fourth moment of a probability density function of the surface.

2. The magnetic storage media of claim 1 having a surface with a positive skewness value in the approximate range of 0.0 to 0.2 and a kurtosis value in the approximate range of 3 to 10.

3. The magnetic storage media of claim 1 in the form of a rigid computer disk.

4. A method of determining optimum skewness and kurtosis values for a surface of a magnetic storage media such as a computer disk, the skewness and kurtosis values determined by the method to reduce static and kinetic friction between the magnetic storage media surface and a read/write head, the method comprising the steps of:

formulating probability density functions for non-gaussian surface roughness distributions with known mean peak heights, standard deviation, skewness and kurtosis values,

modeling parameters of contact of a read/write head with a disk surface including number contact spots, total load force, Young's modulus of elasticity, Poisson's ratio, equivalent ratios of peak asperities,

calculating meniscus force of a lubricating liquid applied to the surface for each probability density function,

selecting a probability density function having a minimum real area of contact and number of contacts, and

extrapolating skewness and kurtosis values of the selected probability density functions having minimum real area of contact and minimum meniscus force.

5. A magnetic storage computer disk having a surface mathematically designed to minimize static and kinetic friction and meniscus forces between the computer disk surface and a disk head placed in contact with the computer disk with an intermediate liquid layer, the computer disk surface comprising a non-gaussian surface roughness distribution with a positive skewness value and a kurtosis value of 5 or greater, said values being extrapolated from probability density functions which



exhibit minimum areas of real contact and minimum meniscus force between the computer disk surface and another surface.

6. A frictional load-bearing object having a surface with a non-gaussian surface roughness distribution, the surface comprising a positive skewness value and a kurtosis value of 3 or greater.

7. A computer hard disk surface with a non-gaussian surface roughness distribution and skewness and kurtosis surface values selected to provide reduced static and kinetic friction and meniscus force between the hard disk and a disk read/write head, the skewness and kurtosis values determined by a method comprising the steps of:

formulating a contact model using probability density functions for non-gaussian distribution of surface roughness to represent real area of contact, normal load and number of contact spots, contact pressure and meniscus force,

plotting curves of probability density functions for surfaces with different peak height ranges, skewness and kurtosis values, and

identifying from the plotted curves surfaces which have the lowest real area of contact and lowest meniscus force and identifying corresponding skewness and kurtosis values.