Correlations between Different Phenomena at the Head Disk Interface

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Abstract

As the head-disk spacing reduces below 5 nm in hard disk drives to achieve increases in data densities, different proximity interactions such as intermolecular, meniscus and electrostatic forces have a greater effect on the ability of the slider to fly stably over the disk. Various experimental studies have been carried out and several models have been suggested to determine which of these interactions plays the dominant role in this loss of stability. This paper attempts to establish correlations between some of these interactions as well as others which may affect the Head-Disk Interface (HDI) reliability by creating a relational chart. Such an organization helps us to draw conclusions about relationships between the existing models, reconcile their inconsistencies and predict possible methods of modeling phenomena which have not yet been modeled completely. It also serves to give a "big picture" of the various efforts being made in the field of HDI reliability and link them together. From this chart, a causal relationship is suggested between the electrostatic, intermolecular and meniscus forces. Understanding this relationship will help to create better models incorporating the effects of these forces on the HDI.

1. Introduction:

To achieve a recording density of 1 Tb/in^2, the head-disk mechanical spacing has to be reduced to 2-3 nm. At this spacing, different proximity interactions such as intermolecular forces, meniscus forces and electrostatic forces influence the ability of the slider to fly stably over the disk. Reduction or compensation of these forces is desired for better HDI reliability and the realization of this recording density goal. Hence, much research has been carried out in the recent past to study these proximity interactions. Different studies (either experimentation or modeling) attribute the loss of stability to one or some of these factors.

However, in this paper, we attempt to show that there is a causal relationship between intermolecular, meniscus and electrostatic forces, and hence, though apparently different in their macroscopic manifestation, they have common origins and so at some level they may not be separate interactions. This is especially relevant as atomic length scales are approached where the connections between these interactions are realized. Hence, a chart has been organized to show some connections between the various interactions and phenomena that affect the HDI. The relevant literature where studies have been reported regarding particular interactions, phenomena or connections are cited along with the description or explanation of the phenomena/connections. The goal here is to give an overview or a perspective of the various efforts made to develop different theories or increase the reliability of the HDI. However, the details, such as descriptions of the studies, figures etc. from each reference are not included for the sake of continuity and focus.

The general surface phenomena/interactions as well as those specific to the HDI are included in the same chart, and connections are made between the two sets. This enables the description of some HDI phenomena in terms of the general models used. Also, there are some phenomena, such as disk-to-slider lube transfer, which have not been studied completely. The organization of the chart and the relative placement of some of the interactions suggest some approaches to modeling such phenomena. Note that the words ‘interactions’ and ‘phenomena’ are used almost interchangeably and really mean ‘interactions or phenomena’, since both are included in the chart.

2. Chart Organization:

Different interactions or phenomena are put in boxes and joined by arrows, which show a causal relationship. The phenomenon to which an arrow is pointing is caused by the phenomenon from which the arrow emanates. Further, the phenomena are arranged from bottom to top as going in scale from microscopic to macroscopic phenomena. Since microscopic phenomena are dealt with by discrete theories and the macroscopic phenomena are dealt with by continuum theories, there is a natural progression from the discrete to the continuum theories as the chart is traversed from the bottom to the top. Each arrow, which indicates the relation between two phenomena, is labeled. These connections are described and explained in the next section in the alphabetical order of their corresponding labels. Solid arrows are used for the connections between phenomena not necessarily restricted to HDI, while dashed arrows signify connections specific to HDI.

3. Correlations:

A brief account of each correlation indicated by a label is given below:

A. Thermodynamic and Chemical Phenomena are based on atomic interactions. Thus they form a theoretical basis for describing the atomic interactions within a material or between different materials and form the basis of all theories. Thermodynamics is concerned with the physical parameters of temperature, pressure, volume and entropy, while chemistry deals with the transfer of electrons, ions, etc. and the associated energies and potentials.

B. The presence of electrostatic forces at the atomic level is a result of the interactions between the charged atomic particles (A1) as negatively charged electrons revolve in specific orbits about the positively charged nucleus in an atom. Specific to the HDI, the presence of electrostatic forces at the macroscopic level is a result of tribocharging [1]-[3], the magnitude of which depends primarily on the electrochemical potential (A2) (thermo-chemical parameter) of the head and the disk surfaces [4]. Recurrent head-disk contact leads to this tribocharging. At this point, no distinction is made between the microscopic and macroscopic manifestation of electrostatic forces, but this will be done later.

C. Since tribocharging is very pertinent to the study of the HDI a short explanation of how it occurs is presented: When two different materials come into contact there is an electron transfer from one material to the other depending upon the work functions of the materials [4]. This transfer occurs until the electrochemical potential of both materials is equalized, which results in an equilibrium of this electron transfer process. Materials have been classified into a "triboelectric" series depending upon the amount of charge they acquire when touched by another material [5].

D. At the HDI, electrostatic force (due to tribocharging) affects the stability of the slider at proximity[6]. It influences the flying dynamics of the slider [2] and the lubricant migration on the disk [7]. Thus, it is detrimental to the reliability of the HDI. Further, tribocharging may cause electrostatic discharge (ESD), due to which the magnetic transducers are damaged [3].

E. Intermolecular forces have their origin in electrostatic forces according to the *Hellman-Feynman theorem*, which states that once the spatial distribution of electron clouds has been determined by solving the Schrödinger equation, the intermolecular forces can been calculated on the basis of straightforward classical electrostatics [8].

   In a material, individual molecules may be permanently polarized or may have induced polarization, which produces a dipole moment. This dipole-dipole interaction between different molecules leads to intermolecular forces [8]. There are primarily three components of intermolecular forces, depending on the nature of the dipole-interaction.

   Keesom force - Permanent dipole – Permanent dipole. This force can be attractive or repulsive.

   Debye force – Permanent dipole – Induced dipole. If there is a molecule with a permanent dipole the electric field due to it induces a dipole in an otherwise unpolarized molecule.

   Dispersion force – Induced dipole – Induced dipole. In a non-polar atom the electron cloud is not perfectly homogeneous, which produces a dipole moment. Although the time average of this charge imbalance is zero the instantaneous dipole induces a dipole in other atoms in proximity to it, and the time average of this interaction is not zero and is responsible for dispersion force [8].

The Debye and dispersion forces are always attractive in nature. The Keesom and Debye forces only exist when there are permanently polarized molecules, while the dispersion forces are *always* present. In the above discussion of intermolecular forces only the contribution of the microscopic electrostatic forces has been considered. Additionally, when tribocharging occurs at the HDI the electric field at the surface of the head or disk is changed due to which intermolecular force will also change. The spatial distribution of all charges under the changed electric field needs to be calculated in order to determine if this change is significant.

F. Surface tension is a direct measurement of intermolecular forces [9]. In a bulk material, an individual molecule is surrounded by other molecules on all sides, and it experiences forces from these molecules. However, for a molecule on the surface of the material other molecules of that material only lie to one side and thus there is an imbalance in the force it experiences, and consequently there is a tension at the interface due to this unbalanced force. This is the basis of surface tension of the material [10]. The surface energy is the amount of energy stored when a surface with surface tension σ is expanded by a unit area. Since the numerical value and the units of both quantities are the same surface tension is also considered as surface energy. Surface energy for a material has two components – polar and dispersive. The dispersive component is always present and is due to dispersive intermolecular forces.

G. The polar component of the surface energy is a result of polar molecules, and thus it can be perceived as a result of Keesom and Debye intermolecular forces. This contributes to most of the observed surface energy in metals. The presence of surface charges also changes the surface energy of materials [11]. Hence, the polar component of the surface energy may change significantly due to tribocharging at the HDI.

H. Friction and wear theories based on adhesion use surface energy [12]-[13] to calculate the work of adhesion, which is a measure of energy required to form a particular interface. Both friction and wear are dependent on the combined effect of hardness and surface energy. Generally, a high surface energy is indicative of more friction and wear. Metals generally have a very high surface energy while non-metals have low surface energy. Surface energy relations are also used to determine the wetting/dewetting thickness of lubricants, which has a direct bearing on HDI reliability.

   The disjoining pressure is the negative of the derivative of the surface energy with respect to the film thickness. It appears in lube depletion and transfer models and also in equations governing thin fluid films due to the dependence of their surface energy on the film thickness [14].

I. Surface energies of different phases/materials dictate wetting or dewetting of a liquid on a substrate and the formation of specific contact angles. Hence, surface energy can be determined from contact angle measurements [14]-[16]. Modeling of a meniscus uses surface energy as a basis along with other continuum mechanics relations [17]-[19]. The meniscus force depends on the surface energy of the meniscus fluid (lubricant or adsorbed water). It should be noted here that the surface energy itself depends on intermolecular and electrostatic forces.

J. Various studies ([17]-[19]) have shown meniscus force to be the main cause of stiction at the HDI. Further, it is also thought to be a major factor contributing to dynamic friction and loss of stability by increasing the touchdown-takeoff hysteresis [17].

K. Just as surface energy of a material is a result of its interatomic interactions, the strength of which is given by the IMF, so is the hardness [12]. Hence, if the IMF is very strong in the material, it is dense and/or hard. It should also be noted that denser materials generally have a high refractive index, which is used to calculate the Hamaker constants used in the IMF calculation. It is found from these calculations that across the same interface denser materials typically have more IMF interaction. Thus the magnitudes of IMF and density/hardness/refractive index are related to each other.

L. Friction and wear are intimately related to hardness of the material. Continuum theories of adhesion and abrasion include hardness as a parameter [12]-[13]. Absolute and relative hardness of the various layers at the HDI have a direct bearing on its reliability.

M. IMF is the basis for properties such as surface energy and hardness on which the friction and wear depends. Thus, IMF indirectly affects the HDI reliability. However, as the head-disk spacing is reduced below 5 nm various studies have shown that IMF directly affects the stability of the air bearing slider [20]-[21]. Multilayer models are used to calculate the Hamaker constants used in the calculation of IMF [20],[22] between the slider and the disk. It has been shown that the magnitude of the IMF is significant as compared to the airbearing forces and the external 'gramload' applied to the slider.

By traversing the chart from labels A – K, we have been able to relate electrostatic forces, intermolecular forces, surface energy and meniscus forces and to appreciate the causal relationship between them. Hence the question of whether electrostatic, intermolecular and meniscus forces independently influence the HDI should be examined closely.

N. Recently, the phenomenon of disk-to-head lubricant transfer has gained some attention, but it has not yet been modeled completely. Some experimental studies [23] of the effect of the disjoining pressure and surface energy of the lubricant on the lubricant transfer (M2) have been reported. Airbearing pressure has also been shown to influence the lubricant transfer [24]. Based on the chart a few more possible contributions to this phenomenon are described.

Atomic distances between the slider and the disk present the possibility of physical transfer of lubricant between the slider and the disk surfaces, which may be modeled on the basis of IMF attraction (L2) of the atoms of the polymer molecules by the slider and disk surfaces using statistical mechanics. Such an approach can calculate the probability of a molecule landing on the slider's surface based on parameters such as activation energy/ bond energy of polymer molecule (L3) and air shear. Electrostatic force may be another cause of the lubricant transfer (L4). There is a charge on the slider and disk surfaces including the polymer film due to tribocharging. Further, head-disk contact, catalytic degradation etc. may lead to the breaking of long chain lubricant molecules into short fragments with unsatisfied bonds, giving them a charge. Thus, this lubricant molecule or fragment may be attracted to the charged slider contributing to the lubricant transfer.

O. Besides the above approach of physical transfer of lubricant by different forces evaporation and condensation (thermo-chemical phenomena) (M1) are used in modeling or explaining the transfer of lubricant from disk to slider [24]-[25]. This model [25] also considers the contribution of disjoining pressure of the lubricant (M2). We note that evaporation or condensation is also a physical transfer, but instead of the above mentioned discrete/ probabilistic approach of lube transfer, it is based on a continuum approach.

P. Lube transfer/pickup is often sighted as one of the factors causing the meniscus (N1) [17]-[18]. However, since the duration of slider-disk contact is usually much less as compared to the time scale estimated to form a lube meniscus (using continuum theory) [21], a continuum lube meniscus picture may not be an accurate visualization of the actual phenomenon. Nevertheless, it has been observed that lube pickup affects the slider stability [26], which may be alternatively explained on the basis of surface energy (N2) since the equilibrium time scale for surface energy is the same as that of intermolecular forces, which is instantaneous even compared to the time scale of slider-disk contact. However, this is a macroscopic empirical theory [13] and a more accurate discrete theory for meniscus force calculation is necessary.

Q. Water adsorption on the surface of the disk from ambient humidity is another reason sighted for meniscus formation [17]-[18]. The adsorption can be explained in terms of thermo-chemical phenomena by describing the affinity of water molecules towards the active sites on the carbon overcoat.

R. The effect of water adsorption on the HDI can be modeled in a similar way as the lube transfer (N) as: due to meniscus formation (P1) or as due to the increase in the surface energy (P2). The adsorbed water occupies the active sites on the carbon overcoat ([14],[27]) thus loosening the lube bonds with the carbon overcoat, and thereby decreasing its viscosity and aiding in lube transfer (P3).

S. Water adsorption is responsible for passivating the catalytic centers responsible for the chemical degradation of the lube [28]. However, it also assists in corrosion of the carbon and magnetic layers.

T. The reactions responsible for disintegration of the lubricant at the HDI can be explained by thermo-chemical phenomena, such as hydrogen bonding, electron transfer etc. [29]-[30](S1). In addition to such mechanisms, the lubricants also degrade under electric fields [31] (S2).

U. The chemical degradation of the carbon overcoat aids in faster degradation of the magnetic layer thereby leading to the loss of data stored [29]-[30] and compromising the HDI reliability.

4. Discussion:

From this chart it can be seen that electrostatic, intermolecular and meniscus forces are related. The meniscus formation is modeled in terms of a continuum theory and the meniscus force depends on the surface tension of the meniscus fluid. This surface energy has two components: polar and dispersive, the origins of which can be traced to electrostatic and intermolecular forces. We further note that the HDI spacing is being reduced to atomic length scales and the period of head-disk contact is much smaller than the time required to form an equilibrium meniscus. Thus we may no longer be able to use the continuum concept of meniscus and instead have to use a more basic theory (which occupies a lower position in the chart) to calculate this force. The chart suggests that the meniscus force can be modeled directly in terms of intermolecular and electrostatic forces. Since the time scales for these interactions are far less than the duration of the head-disk contact, the equilibrium theories for these interactions could be used. However, since the intermolecular and electrostatic forces depend on the position of individual atoms and molecules (of DLC and lube) at the interface and the distance between them, the calculation of the exact force can be commensurately difficult, and a statistical mechanics/Monte-Carlo type approach may need to be considered. It can be appreciated that the meniscus force is a direct result of intermolecular and electrostatic forces, and hence as the length and time scales become smaller it can be calculated directly in terms of these interactions.

The "mesoscopic" length scales lie between the microscopic and macroscopic ones and in these there is an inter-relation of the microscopic and macroscopic theories. The HDI length scales lie in this region as we are simultaneously using macroscopic theories such as the continuum Reynolds equation with modified parameters derived from microscopic theories like the Boltzmann equation (F-K model). From the chart it can be seen that the macroscopic concepts like surface energy and hardness have their roots in microscopic phenomena, and thus it can be said that any theory which can calculate these macroscopic parameters from the microscopic phenomena is mesoscopic in nature. Hence, theories for disk-to-slider lube transfer, water adsorption and chemical degradation, which can be explained in terms of intermolecular attraction or ion/electron exchange etc., occupy the place in the chart corresponding to mesoscopic theories.

5. Conclusions:

A chart has been organized to show the connections between different interactions or phenomena occurring at the HDI. Such an organization, in addition to providing an overview of the work in HDI reliability, also acts as an instrument to help understand the relationship between different phenomena, and it can be used to suggest modeling approaches to those phenomena that have not yet been modeled completely.

The chart has been organized with microscopic phenomena at the bottom proceeding towards macroscopic phenomena at the top showing the causal relationships between different phenomena. By observing this causal relationship it can be appreciated that meniscus force depends upon the intermolecular and electrostatic forces, and as the time and length scales at the HDI reduce, the meniscus force can be calculated directly in terms of the intermolecular and electrostatic forces. The disk-to-slider lube transfer has not yet been modeled completely. Possible approaches for modeling this phenomenon are suggested by the chart.

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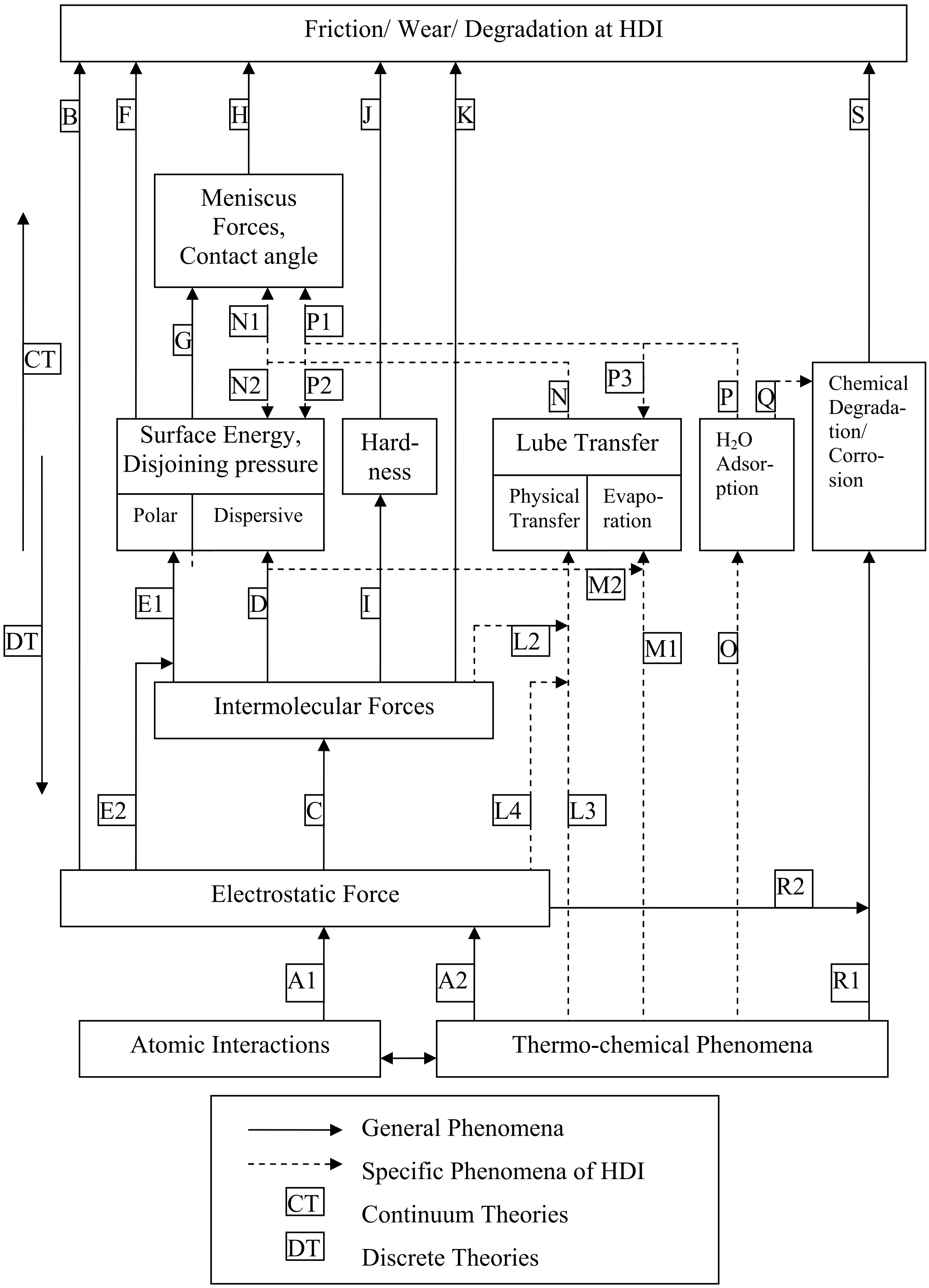
Chart:


Friction/ Wear/ Degradation at HDI
B
F
H
J
K
S
Meniscus Forces, Contact angle
CT
G
N1
P1
N2
P2
P3
N
P
Q
Chemical Degrada-tion/ Corro-sion
Surface Energy, Disjoining pressure
Polar
Dispersive
Hard-ness
Lube Transfer
Physical Transfer
Evapo-ration
H2O Adsor-ption
DT
E1
D
I
M2
L2
M1
O
Intermolecular Forces
E2
C
L4
L3
Electrostatic Force
R2
A1
A2
R1
Atomic Interactions
Thermo-chemical Phenomena
General Phenomena
Specific Phenomena of HDI
CT
Continuum Theories
DT
Discrete Theories