AIR LUBRICATION IN HARD DISK DRIVE

Mechanics of Contact and Lubrication
Department of Mechanical & Industrial Engineering
Northeastern University
Boston, MA 02115
Binwei YAN
Yan.bi@husky.neu.edu
Qiang YAN
Yan.q@husky.neu.edu
Yuyao HE
He.y@husky.neu.edu

Abstract

Hard disk is a widely used device for digital data storage. It has been studied and developed for more than thirty years. One of the research branches is the lubrication problem. In this research report, the overall review of the structure of the hard disk and the ways of lubrication is introduced. Specifically, the report is focus on the lubrication between the slider and platter. A new modified Reynolds equation and the equations of motion are explained in this paper. Based on these equations, a way to improve the efficiency of lubrication and performance of the hard disk are provide in the last part of the paper.

Key words: hard disk, lubrication, air bearing.

1. Introduction:

Although the SSD (Solid-State Drive) has been developing very well in the past few years, the HDD (Hard Disk Drive) is still the most important data storage device because of its great price-performance ratio. The biggest difference between SSD and HDD is the storage medium. The SSDs use flash memory while HDDs use platters, which are covered with magnetic materials.

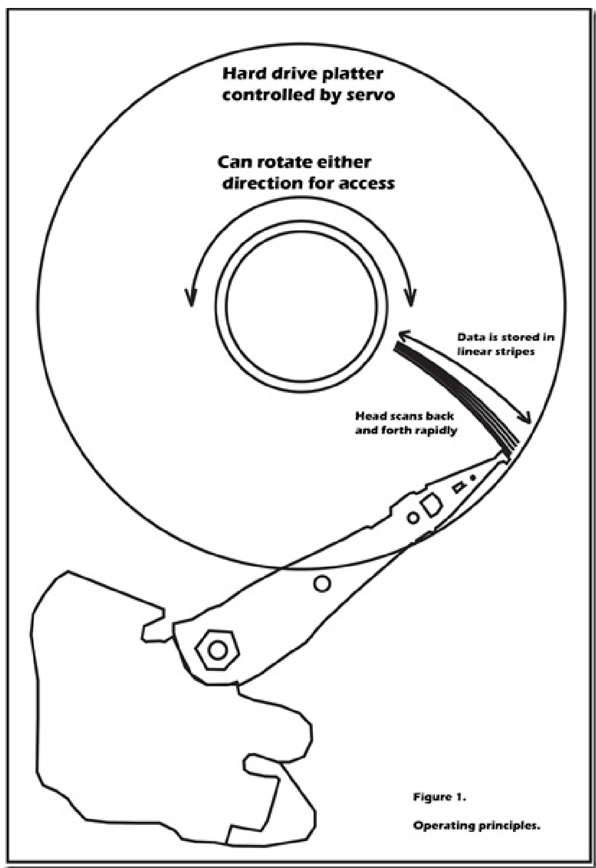

Fig. 1 The read & write head and the platter [1]

As we see in Figure 1(Rouviere, 2009), inside a single-disk hard drive, we can see 3 components: an arm with a read and write head in front, a platter and a spindle. If we simplify this hard disk drive to a model, we might describe its working process as this:

The platter rotates around the spindle and the actuator arm is controlled by a voice coil actuator[1] (Mueller, 1998). This combination enables the read and write head go to anywhere on the platter's surface. While the head slides over the platter, the data, ones and zeros can be stored into or picked up from the magnetic domains.

Unlike the relationship between the magnetic head and tape in cassette players, the head and the platter in hard disks cannot be contacted to each other because the platters spin at speeds up to 15,000 rpm[2]. (Blount, 2007) At this speed, if the head really touches the platter, the head is very likely to be damaged and so is the platter. Meanwhile, the distance cannot be too long. If the head and platter is too far from each other, the data cannot be written or read because of weak magnetic flux. Therefore, the distance between the head and platter needs to be only 3nm.

When the HDD is powered on, the platter starts to rotate around the spindle with a high speed. (Joshuamarius**,** 2006) This research project will study how air works as the lubricant between the read and write head and the platter.

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[1] Or a step motor.
[2] Today, hard disk drivers usually work at 4200rpm to 14400rpm.

2. Surface Roughness:

Before talking about the air lubrication between the head and platter, it is necessary to talk about the construction of the platter and the head, especially the surface roughness.

2.1 The Platter

Basically, the platter is a circular disk made with nonmagnetic material (aluminum or glass and ceramic) covered with several layers:

Lubricant Layer: This is the topmost layer of the platters and is made of a substance similar to Teflon. This layer is used to protect the Magnetic layer.

Carbon: There is a layer of sputtered carbon just below the lubricant layer. This layer is also used to protect the Magnetic layer.

Magnetic Layer: This is below the layer of carbon. This is the core part of the platter, it holds all data. (HD Doctor Blog, 2008)

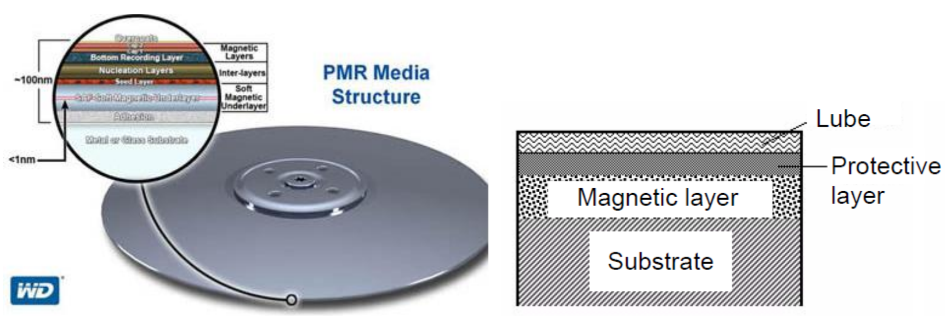

Fig.2 Layer structure of the platter (Western Digital, 2011)

2.2 The Head

The head is an interface between the magnetic media where the data is stored and electronic components in the hard disk. The heads convert the information, which is in the form of bits to magnetic pulses when it is to be stored on the platter and reverses the process while reading.

The heads are the most sophisticated part of the hard disk. Each platter has two read/write heads, one mounted on the top and the other one at the bottom. These heads are mounted on head sliders, which are suspended at the ends of head arms. The head arms are all fused into a singular structure called actuator, which is responsible for their movement. (HDD Basic, 2010)

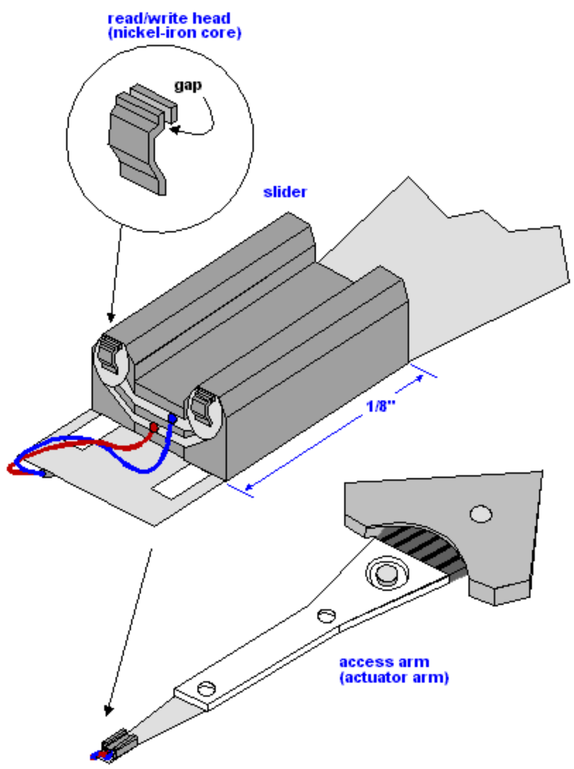

Fig.3 Structure of the read & write head (PCmag.com,2006**)**

3. Lubrication

The distance between the platter and the read and write head is called magnetic space. The air bearing is used in this space to reduce wear and carry partial load of the slider. To some extent, the analysis of this air film is the important part of the whole research of hard disk. Here we start the analysis from governing equation first.

3.1 The original Reynolds equation

The equation that governs the generation of pressure in the lubricating film is known as the Reynolds equation.

$$\frac{\partial}{\partial x}\left[\frac{ph^3}{\eta}(\frac{\partial p}{\partial x})\right]+\frac{\partial}{\partial y}\left[\frac{ph^3}{\eta}(\frac{\partial p}{\partial y})\right]=6\frac{\partial}{\partial x}(Uph)+12\frac{\partial}{\partial t}(ph)$$

Where x, y are the spatial coordinates

x is in the sliding direction

t: time

η: absolute viscosity of the gas

U: sliding velocity of the moving bearing surface

p: the local pressure of the gas

h: local film thickness

The Reynolds equation is based on the continuum theory of fluid mechanics. If the mean free path of the molecules is large compared to the film thickness, free molecular flow occurs. However, if the mean free path of the molecules becomes comparable to the film thickness, the gas does not behave entirely as a continuous fluid, so we should use the modified Reynolds equation.

3.2 The modified Reynolds equation

Knudsen number, $M_\ell = \lambda / h$, is the criteria for the boundaries of the regimes between continuum flow, slip flow, and free-molecular flow.

Continuum flow: M_ℓ<0.01

Slip flow: 0.01< M_ℓ <3

In 1959, Burgdorfer, derived the modified Reynolds equation in the slip-flow regime by using modified boundary conditions. Based on his paper, the modified Reynolds equation becomes:

$$\frac{\partial}{\partial x}\left[ph^3(1+\frac{6aMp_a h_m}{ph})\frac{\partial p}{\partial x}\right]+\frac{\partial}{\partial y}\left[ph^3(1+\frac{6aMp_a h_m}{ph})\frac{\partial p}{\partial y}\right]$$
$$=6\eta_a(Uph)+12\eta_a\frac{\partial}{\partial t}(ph)$$

The molecular mean free path at ambient conditions λ_a, for air is 0.064 μm, if M<0.01 or h_m >6.4 μm for air films, then we can use the basic Reynolds equation for continuous fluid. If 0.64 $\mu m < h_m$ <0.025 μm for air. Then we should use the modified Reynolds equation. Based on the experimental data, the modified Reynolds equation applicable in the slip-flow regime can be used accurately up to an air-film thickness of about 0.025 μm. In general, the air film between the head and platter is an ultrathin spacing that in some cases it can be several nms. As a result, the modified

Reynolds equation should be used in our analysis. (Bhushan,1996)

3.3 The modified Reynolds equation in hard disks

The disk slider is attached to a leaf spring suspension that provides the three degrees of freedom for excursion (one degree of translation freedom in the direction perpendicular to the disk surface and two degrees of rotational freedom in the orthogonal directions-pitch and roll). This is a case of hydrodynamic lubrication and the elastic deformations of the bearing members are negligible, unlike flexible media. In general, the slider may be oriented with respect to the disk velocity vector, that is, it has a skew angel that would result in velocity components, both in the x and y directions (U_x, U_y). Therefore, an additional term appears in the right-hand side of the Reynolds equation given by:

$$\frac{\partial}{\partial x}\left[ph^3\left(1+\frac{6aMp_a h_m}{ph}\right)\frac{\partial p}{\partial x}\right]+\frac{\partial}{\partial y}\left[ph^3\left(1+\frac{6aMp_a h_m}{ph}\right)\frac{\partial p}{\partial y}\right]$$
$$=6\eta_a\left[\frac{\partial}{\partial x}(U_x ph)+\frac{\partial}{\partial y}(U_y ph)\right]+12\eta_a\frac{\partial}{\partial t}(ph)$$

x is in the sliding direction
t: time
η: absolute viscosity of the gas

U : sliding velocity of the moving bearing surface

p: the local pressure of the gas

h: local film thickness

$$M=\lambda_a/h_m$$

M : Knudsen number at ambient condition

λ_a : molecular mean free path

h_m : reference film thickness

The free body diagram of the head is as followed:

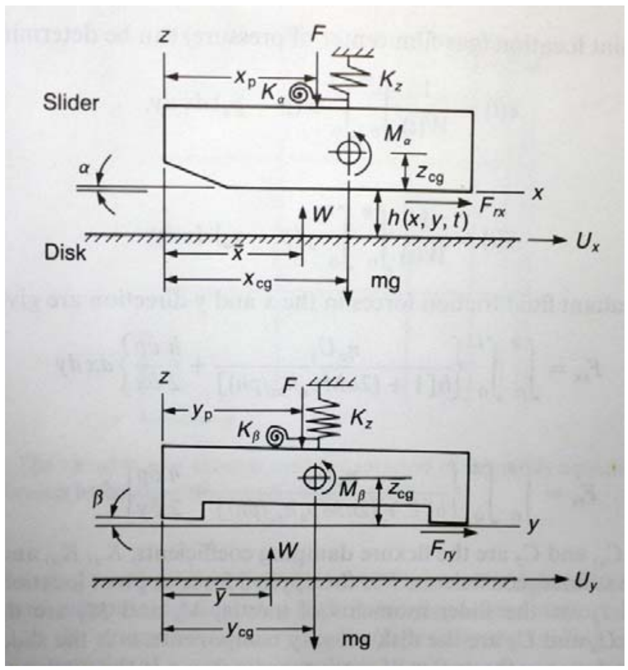

Fig.4 the free body diagram of head

The rigid body equations of motion for the slider attached to a flexure that provides three degrees of freedom is governed by:

$$m\frac{d^2z}{dt^2}+C_z\frac{dz}{dt}+K_z z+mg+F=W(t)$$

$$I_\alpha\frac{d^2\alpha}{dt^2}+C_\alpha\frac{d\alpha}{dt}+K_\alpha\alpha+M_\alpha+(F+K_z z)(x_{cg}-x_p)+F_{rx}z_{cg}$$
$$=(x_{cg}-\bar{x})W(t)$$

$$I_\beta \beta \frac{d^2\beta}{dt^2} + C_\beta \frac{d\beta}{dt} + K_\beta \beta + M_\beta + (F + K_z z)(y_{cg} - y_p) + F_{ry} z_{cg}$$
$$= (y_{cg} - \overline{y}) W(t)$$

m : head mess
F : the applied force

C_z, C_α, C_β : the flexure damping coefficients

K_z, K_α, K_β : the flexure stiffness coefficients

I_α, I_β : slider moments of inertia

M_α, M_β : static moments

x_{cg}, y_{cg}, z_{cg} : center of mass coordinates
α : pitch angle

β : roll angle

Where the bearing load is given by

$$W(t) = \int_0^B \int_0^L (p - p_a) d_x d_y$$

The boundary conditions generally used are ambient pressure at the edges of the head slider. In most of the analyses reported in the literature, flexure effects (stiffness, damping), static moments, or fluid friction forces are not included. (Bhushan,1996)

Full nonlinear analysis of the slider dynamics requires a simultaneous solution. The solution can be found by numerical approach.

3.4 The application of equation of motion and Reynolds equation

In a design process, in general, a certain height (magnetic spacing) has to be designated first. Then we substitute the value of height into the Reynolds equation. From this procedure, the pressure can be obtained. Then according to the equation of motion, we can get a new height. Then we put this new height into the Reynolds equation again. We do this whole procedure repeatedly until the difference between the height we expected and the height we get from the governing equation is really small.

4. The effective way to lower the magnetic spacing

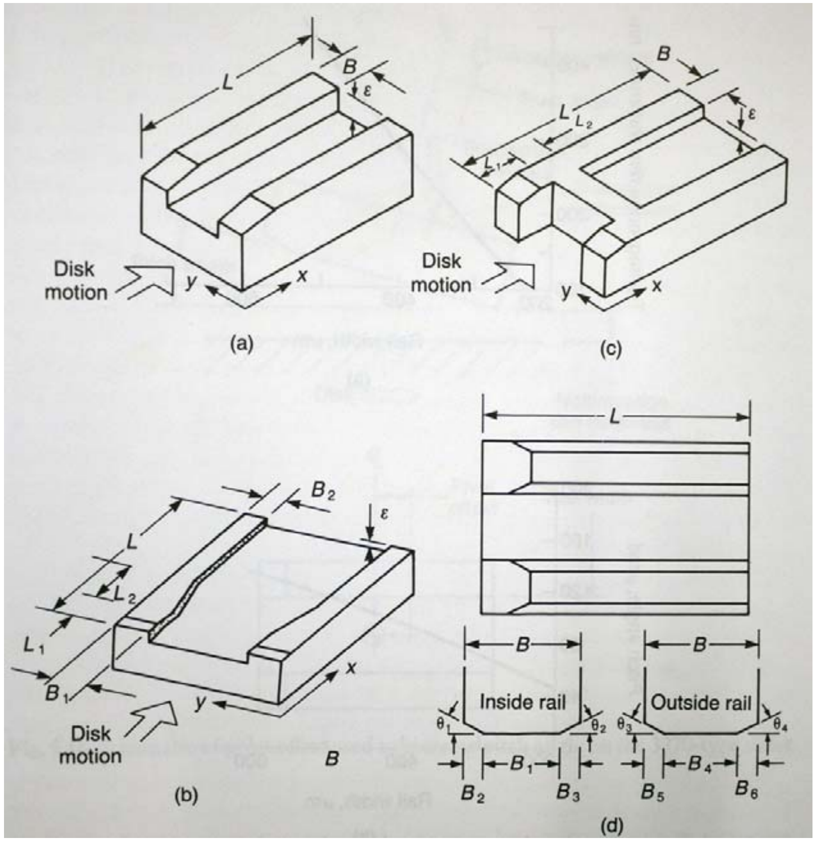

Fig.5 (a) Schematic of conventional IBM 3370-type two-rail taper-flat slider. (b) Schematic of IBM 3380 K-type shaped-rail slider. (c) Schematic of zero-load or self-loading slider. (d) Schematic of transverse pressurized contour (TPC) slider.

In general, the development of the hard disk design is tending to reduce the fly height of the slider. A conventional self-acting air-bearing slider was first introduced in IBM 3370 drives (355-mm disk diameter) and is shown in Fig.5 (a). It is composed of two rails with a wide ambient pressure success separating the air- bearing pads. Each rail has a taper-flat configuration. The front taper serves to pressurize the air lubricant, while some of the lubricant is lost through leakage to the side. In this paper, this air-bearing design will be referred to as 3370-type.

The flying attitude of the air-bearing slider is described by three important parameters: the trailing-edge (minimum) film thickness, pitch angle, and roll angle. Lower film thickness used in future products are achieved by changing one or more of the many slider parameters in a way that reduces the load bearing capacity of the slider. Reducing the slider rail width is often used to lower the trailing-edge film thickness of the slider. Reducing the rail width also lowers the pitch angle. Lowering the film thickness and the pitch angle at the same time the average film thickness is reduced, which increases the chance of slider to disk contact. If the pitch angle is increased as the trailing edge film thickness is decreased, the drop in the average film thickness could be reduced or eliminated. This would minimize the interaction of the slider with the disk surface. An increased pitch angle design can be achieved today by offsetting the pivot point toward the trailing edge of the slider. This approach to increasing the pitch angle is limited.

A novel shaped rail design referred to as the shaped-rail design can attain increased pitch angles, independent of film thickness, with a central suspension attachment. Unlike conventional taper flat designs, each side rail has a widened leading edge rail width that is flared down to a small rail width toward the trailing end.

In recent years, trends have been to go to smaller low mass sliders and to apply only a small load on the slider in order to minimize disk wear. Unfortunately, with conventional two rail sliders, the air-bearing stiffness is somewhat proportional to the load. (Bhushan,1996)

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