*Invited Paper*

# Thermal and Fluid Dynamic Study on Voice Coil Temperature Rise during Faster and Frequent Seeking in Hard Disk Drives

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## Abstract

The coil temperature of head actuators is a dominant parameter for seek performance and reliability of disk drives. We formulate its basic relation from power consumption to temperature rise. We clarify the power consumption in temperature changing system, and discuss on "Thermorunaway". In the actual operating drives, we calculate effective power consumption. To calculate thermal resistance in actual drives, we excute internal flow numerical analysis and thermal conductivity simulation. To reduce thermal resistance, we propose internal flow modification as improving impinging flow against the coil. The change improves thermal resistance by around 30% in simulation. The experimental results agree the calculated results.

**Keywords:** Hard Disk Drives, Voice Coil Motor, Temperature rise, Fluid analysis, Heat Transfer, Thermal resistance

## Introduction

ENTERPRISE Hard Disk Drives of 10k or 15krpm prioritize random access performance for mission-critical applications. This causes very frequent and faster seeking, and power consumption of the voice coil is enormous. The coil temperature rise affects two issues; one is decreasing seek performance caused by resistance increase; the other is reliability problems as, coil outgassing etc.

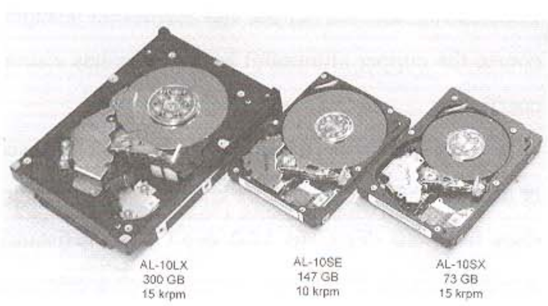


**Figure 1.** Enterprise Hard Disk Drives

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Therefore, the server performance depends on the temperature rise of voice coil. However, there is a little literature on this issue of disk drive actuators.

In this paper, we will clarify the voice coil temperature rise issue. We will begin with the relations between power consumption and temperature rise. By varying the coil resistance due to temperature rise, we define and estimate the actual power consumption. Applying this method, we will estimate the actual power consumption of the enterprise HDDs during very frequently seeking. Next, we will calculate the overall heat transfer by using internal flow analysis and heat conductivity analysis. Using these results, we will discuss how to decrease thermal resistance of actual HDD. Flow optimization will be presented.

## Influence of coil Temperature Change

The head actuator contains heads, arm assembly, voice coil and magnetic circuit. The resistance of voice coil is from 5 ohm to 10 ohm. It depends on the supply voltage.

As is well known, the coil resistance depends on the temperature. The temperature coefficient is 0.42%/degreeC for cupper and aluminum wire. Of course the cupper aluminum hybrid wire has a same coefficient.

Table 1 shows a basic performance comparison of actuator during temperature change. If temperature rises from 20 deg.C to 100 deg.C, the resistance increases around 25%, and it reduces seek acceleration of 25 %. Therefore, the coil temperature is a dominant parameter for access performance.

We can note the temperature rise; one is a atmosphere temperature change, and the other is coil temperature rise due to Joule's heat dissipation after frequent seeking. Usually, the drive controller monitors temperature, and when coil temperature is higher, it controls seek characteristics slower.

In this manner, coil temperature is a critical parameter for seek performance and reliability. In the next chapter, we will study it quantitatively.

**Table 1.** Seek performance during temperature change

| Temperature ( deg.C ) | Resistance ( ohm ) | Current at 11V ( A ) | Acceleration ( Gs ) |
|---|---|---|---|
| 20 | 6 | 1.833 | 200 |
| 100 | 8.016 | 1.372 | 149.7 |

## Temperature Rise under Resistance Change

Generally, temperature rise of the voice coil is described as follows,

$$\Delta T = \theta P \qquad (1)$$

*where,*

$\Delta T$ : Temperature rise (deg.$C$)

$\theta$ : Thermal resistance (deg.$C/W$)

$P$ : Power consumption ($W$)

The thermal resistance is decided by the integration of heat conduction, heat transfer to the air, shown in Figure.2. Power consumption of the voice coil is defined,

$$P = Ri^2 \qquad (2)$$

*where,*

$R$ : Electric resistance of voice coil ($\Omega$)

$i$ : Driving current ($A$)

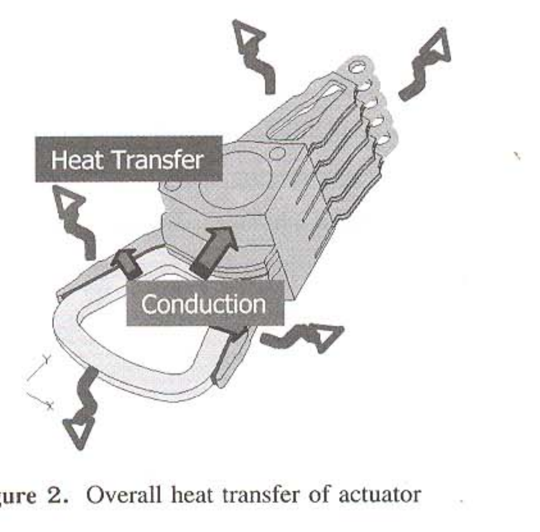



**Figure 2.** Overall heat transfer of actuator

However, electric resistance depends on the temperature, as,

$$R = (1 + c\Delta T)\,R_0 \qquad (3)$$
$$P = (1 + c\Delta T)\,P_0 \qquad (4)$$

$P_0, R_0$ : Properties at initial temperature

$c$ : Resistance temperature coefficient
= 0.0042 /deg.C (copper, aluminum coil)

Therefore, power consumption depends on the temperature rise. This makes it difficult to know the exact power consumption value by only monitoring the running current.

Using Eq. (1)-(3), we can obtain,

$$\Delta T = \theta R_0 (1 + c\Delta T) i^2 = (1 + c\Delta T)\,\theta P_0$$

We can solve temperature rise as,

$$\Delta T = \frac{\theta P_0}{1 - c\theta P_0} \qquad (5)$$

Equation (5) means that the actual temperature rise is higher than simple calculation using power consumption of the initial temperature. In the other words, power consumption is increased due to resistance increase by temperature rise. In general, we can estimate the actual temperature rise by using Eq.(5), or numerical simulations.

Figure 3 shows the comparison between Eq.(1) and (5). By increasing the driving current, both results differs largely. This difference is caused by the power consumption increase. You should note this calculation is assumed by a constant current source. In the actual system, the power supply cannot maintain a constant current by the resistance increase.

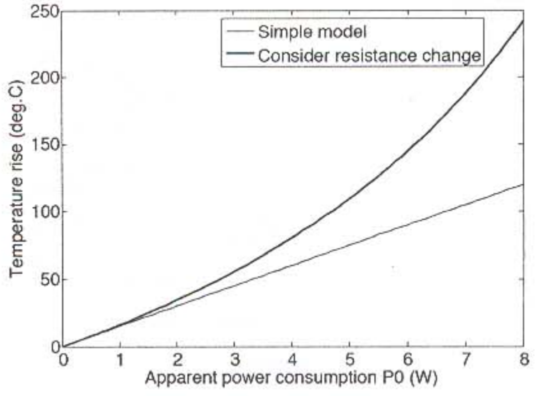


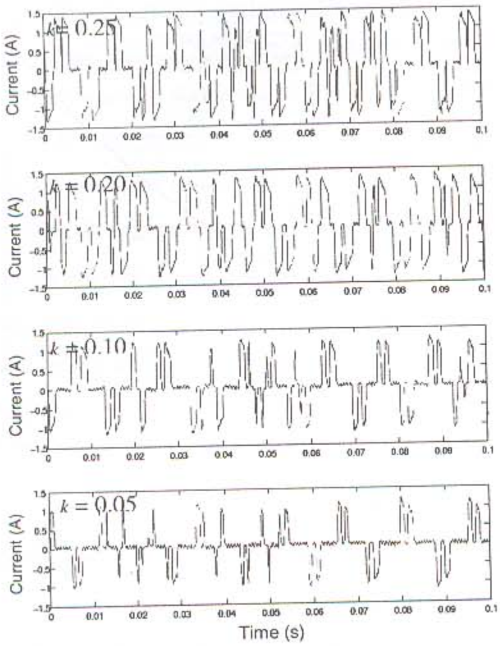

**Figure 3.** Temperature rise considering resistance change

## Power Consumption of HDD Operating

In this section, we will quantify a power consumption of VCM at initial temperature $P_0$ of actual working HDDs. It depends on the seeking condition. Exactly, total power consumption includes power amplifier, electronics part. Here we will consider the power dissipation at VCM coil part. We have to measure the VCM current during various seeking. Figure 4 shows the time history of the coil running current of a 3.5-inch FF 15krpm HDD. The average seek time is 3.5 ms. The figure shows from very frequent and fastest seeking to the lower duty and slower seeking. We can describe the equivalent power consumption as follows,

$$P_0 = k\,R_0\,i^2 \qquad (6)$$

$k$ : Seeking frequency and intensity parameter
$= 0 - 0.3$




$k$: seek duty parameter in Eq.(6)

**Figure 4.** Coil current waveform of various duty seeking in actual HDDs

Using the current waveform of Figure.4, we numerically calculated $P_0$. According to our experiment, the maximum value of k is 0.25, and the lowest is 0.05. Of course, in on-tracking condition without any seeking, the power consumption of the coil come on zero. Please note actual P is the larger value due to temperature rise as I mentioned. In this experiment, the maximum coil temperature at 60 °C ambient temperature exceeds 100 °C, it corresponds about 30% increase of power consumption comparing to 20 °C condition. In this exact calculation, the equivalent $k$ corresponds to 0.33.

## Overall Heat Transfer from Coil

If we consider thermal resistance, we have to know the overall heat transfer. Figure 2 shows the heat transfer route and Figure.7 indicates the

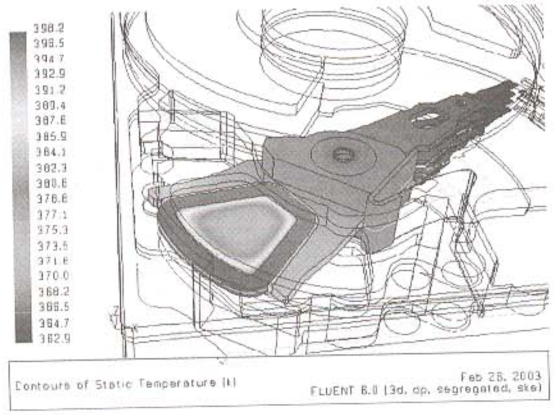



**Figure 5.** Calculated temperature distribution in the actuator

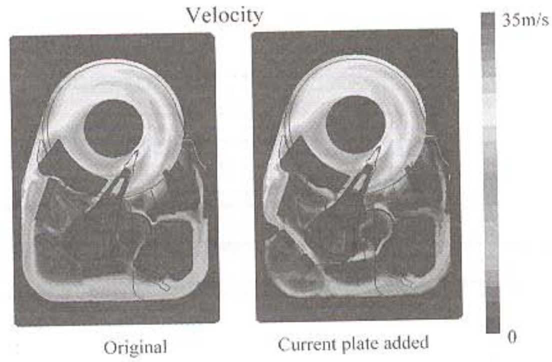



**Figure 6.** Computed air-flow velocity distribution

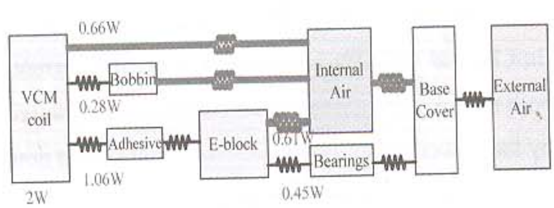



**Figure 7.** Breakdown of overall heat transfer

equivalent model of the heat transfer. The heat is generated at the coil part. The heat transfer route is next two; one is a heat conduction to E-block, and finally transferred to the air, the other is transferred to internal air directly by flow transfer. The resistor, shown by the thin line is a thermal conduction, which can be calculated with relative ease. But the resistor, shown by the heavy line is governed by heat transfer of the internal flow. To calculate heat transfer due to flow is not so easy. It depends on the flow velocity and the intensity of turbulence. We have to compute it by the complete flow simulation. Since the E-block (carriage) has a comb-shaped aluminum alloy, it is a good heat radiator in faster internal flow. However, thick adhesive between the coil and the E-block disturbs the heat transfer.

## Internal Flow Computation

To calculate the flow heat transfer coefficient, we analyze the drive internal flow. We have two ways to compute it. One is a complete model simulation of the HDD. Multiple disks and fully three dimensional actuator and drive mechanisms are modeled with around 20 million meshes.

We applied Fluent 6 for the flow and thermal conductivity computation. This complete analysis is indispensable for calculating heat transfer coefficient, but the CPU time is huge. Therefore, usually, after computing the heat transfer coefficient of internal flow, we sometime apply actuator heat conduction model. The surface heat transfer coefficient is given as surface boundary condition. This technique is suitable for the actuator design change by relatively short CPU time.

Figure 6(a) shows the velocity distribution of initial condition. In the actual drives, there is a bypass flow around the magnetic circuit for reducing the arm-impinging flow. But, the flow velocity around coil is relatively lower, it suggests coil cooling capability is inadequate. The flow velocity at tips of E-block is around 30 m/s, the velocity at vicinity of coil is less than 1 m/s. Generally, since heat transfer coefficient is proportional to square root of velocity, the heat transfer coefficient of coil part is less than 1/5 of the arm tip. In the numerical simulation, the heat transfer coefficient at arm-tips is about 130 $W/m^2K$, very higher value.

Figure 5 shows the simulated temperature distribution. We can see the coil part is the highest temperature and the next is the E-block. However, there is a temperatures difference between coil part and E-block. This is due to lower thermal conduction of thick adhesive between the coil and E-block. This means overall heat transfer is insufficient. Using these results, I'll show the example of the breakdown of overall heat transfer in Figure 7. We can see that the around half heat is transferred to the air directly, and the residual half is transferred through the E-block.

## Coil Cooling Improvement

In the actual HDDs, the temperature rise under severe seeking sometimes exceeds the specification. To gain wider margin of coil temperature, we attempted the flow optimization. The basic idea is improving coil cooling directly by the coil impinging flow. Generally, for the purpose of magnetic circuit optimum design, side yokes are located around the coil. This side yoke affects the flow isolation around the coil. For this purpose, we made a triangle current plate in the bypass flow. The flow path is designed through between side yokes around the coil.

By the plate, the bypass flow impinges the coil directly, and the heat transfer increase is expected. Figure 6(b) compares the flow computation before and after improvement.

Table 2 compares the thermal flux between initial and improved condition. At initial condition, the heat to the air and E-block is equal, but after improvement, the heat to the air is increased about 2/3 of total heat flow. Table 3 shows the overall effect of internal flow optimization. In the experiment, thermal resistance was improved by around 30%. This corresponds with actual temperature being lowered by 20 deg.C. This difference is very large in reliability, and seek performance.

**Table 2.** Heat flux comparison for flow improvement

| | Initial | Flow improved |
|---|---|---|
| Heat to internal air | 51.7% | 66.5% |
| Heat to E-block | 48.3% | 33.5% |

**Table 3.** Calculated and measured temperature rise

| | Initial | Improved | Imp/Init |
|---|---|---|---|
| Thermal Resistance Measured $\theta_{exp}$ deg.C/W | 15.0 | 10.7 | 0.713 |
| Thermal Resistance Calculatec $\theta_{calc}$ deg.C/W | 18.3 | 12.8 | 0.700 |
| Temp. rise at P=4.6W(Measured) ΔT deg.C | 69 | 49 | |
| Temperature at 60 deg.C anvi. T deg.C | 129 | 109 | |

Comparing with calculated result, the thermal resistance differs around 20%. This may be due to whole route consideration at calculation or flow analysis accuracy. Or it may be affected by the accuracy of calculation and the measurement. As the computation model is very huge, we have to decrease the mesh number. However, there is a great agreement with the relative improving ratio of (Improved Thermal Resistance /Initial TR).

## Conclusion

We studied the VCM coil temperature rise of the HDDs.

We can conclude as follows,

1. We formulated temperature rise under resistance change due to temperature change. The results show that resistance change is negligible, and we clarify the mechanism of "Therorunaway" of VCM coil.

2. We estimated VCM power consumption in various seeking condition by numerical integration of current waveform of actual HDDs. The equivalent power consumption is described as 5-30% of ideal Joule dissipation using DC current.

3. We measured and simulated actual coil temperature rise. Using the result of internal flow computation, we modeled the actual overall heat transfer. Basically, half of the heat is transferred through E-block. and half is to the air directly. And we can see the flow around the coil is relatively lower velocity.

4. To improve the coil thermal resistance, we made flow improvement around the coil. The results show about 30% improvement of thermal resistance and 20°C decrease of coil temperature.

These results are useful for achieving highly reliable and faster HDDs.

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