THERMAL RISE PREDICTION AND AN INNOVATIVE APPROACH
OF SENSING TEMPERATURE RISE IN VOICE COIL MOTORS

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Abstract- The paper covers the following topics:

1) Voice Coil Motor (VCM) characteristics in a disk drive environment.
2) VCM operation in a disk drive servo environment.
3) Current profiles in VCM seek operations.
4) Thermal rise prediction simulations.
5) An innovative approach of utilizing VCM as a thermal sensor.
6) Collected data presentation and simulation results

1) Introduction

Achieving faster seek times has always been a requirement for the hard disk drive industry. Higher levels of VCM current are required to move the VCM at faster speeds. However, higher levels of current may cause thermal problems within the coil since excessive heat may cause the coil adhesive to start outgassing which affects the reliability of the drives. Additionally, the performance of the Head Stack Assembly (HSA) may suffer in an excessive heat environment. For example, the VCM resonances will shift to different frequencies and cause settling and stability problems.

2) Background

As faster access times have become the requirement, there has been a need to sense or calculate the temperature of the coil to prevent the aforementioned problems. A temperature sensor may be utilized for this purpose. An alternative to using a sensor would be slowing down seeks to stay below the acceptable temperature level for the worst case condition. However, in order to address the worst case condition the VCM could be slowed down prematurely, thus increasing average seek and access time. The use of temperature sensor is a viable solution but this can be costly and contradicts the low cost objective of today's hard disk drive designs and manufacturing practices.

As discussed in an earlier paper [1] thermal rise could be measured and calculated indirectly in laboratory environment. However, this method cannot be used in the field. Thus, a no-cost 'internal' sensor is desired for sensing the thermal rise of the VCM coil when the disk drive is in operation such that VCM performance is optimized.

3) VCM Characteristics in Disk Drive Environment

Traditionally, VCM is used in hard disk drives as the actuator to position the read/write head over desired track locations. For optimizing VCM performance, torque constant (K_t) and coil resistance (R_w) should be selected accordingly. For each hard disk drive application electro-magnetic analyses are utilized to determine the optimized motor torque constant (K_t) and coil winding resistance.
Figure 1 depicts a typical VCM coil structure as used in the hard disk drive.

![Diagram of VCM Coil Structure](image)

**Figure 1: VCM Coil Structure**

A magnetic field is set up by two magnetic plates sandwiching one or two permanent magnet(s), which are usually made up of high grade materials such as Neodimum Iron Boron (NeFeB). Typically, the magnetic strength of such magnets that are used in hard disk drives is around 44-48 MGOe (Mega Gauss Orsted). A wound coil which is attached to the actuator is overmolded by a plastic structure (called a bobbin). The coil is placed between the two permanent magnets. Since the magnetic field lines are perpendicular to the current moving in the coil, there will be a force generated by the interaction of the magnetic field and the current carrying coil to move the actuator. Such a relation can be expressed as [2],

\[ F = i \times L \times B \]  \hspace{1cm} (1)

where,

- \( F \) = generated force (N)
- \( i \) = current flowing through the coils (Amps)
- \( L \) = length of the coil (m)
- \( B \) = magnetic field strength (Tesla)

If \( L \) and \( B \) are completely perpendicular to each other, then the generated force is equal to:

\[ F = n i L B \]  \hspace{1cm} (2)

where \( n \) is the total number of coil turns with length \( L \).

VCM torque \( (T_{VCM}) \) is defined as the generated force times the average radius of the active part of the coil \( (r) \). Combining equation (1) with equation (2) result in,

\[ T_{VCM} = Fr = n i L Br \]  \hspace{1cm} (3)

In hard disk drive environment current is used as the control signal to the VCM. Thus the control torque generated within the VCM \( (T_{\text{control}}) \) by the control signal is equal to:

\[ T_{\text{control}} = K_i i \]  \hspace{1cm} (4)

Where \( K_i \) is defined as the torque constant of the actuator.

Equating equations (3) and (4) yields:

\[ K_i = n L B r \]  \hspace{1cm} (5)

\( K_i \) has units of Nm/Amp or oz-in/Amp. The magnetic strength \( (B) \) is a material constant and is adversely affected by higher temperature. As a result \( K_i \) will be lower at higher temperatures.

An additional factor which affects \( K_i \) within the operating range of a VCM seek angle is the non-uniformity of the magnetic field \( (B) \) at the ends of the
magnets. Figure 2 shows a typical $K_v$ variation plot versus VCM location expressed in terms of move angle range.

![Figure 2: Torque Variation Curve with VCM Location](image)

The torque constant has a peak value in the middle of the move angle range, which is known as the middle disk location (MD) of the VCM. The torque constant at both ends of the curve (referring to the inner disk location (ID) and the outer disk location (OD)) are less than that in the MD, due to the non-uniformity of magnetic flux at the ends of the magnets. Figure 3 depicts this situation.

![Figure 3: Non-uniform Magnetic Field Lines at Edges of Magnetic Plates](image)

4) VCM Operation in Disk Drive Servo Environment

In hard disk drive, the servo system can typically be modeled as a block diagram:

![Figure 4: Typical Servo Model](image)

In a simulation, the electro-magnetic properties of the VCM coil can be modeled simply as the inverse of coil winding resistance ($1/R$). In most disk drive VCM systems, the power drive is current driven. Thus, the inductance effects on current rise are insignificant for non-saturated voltage inputs. The current is an output of the driver model and is called the control current of the VCM. For different control current profiles both the thermal and mechanical responses will be different. This will be discussed in the next section.

Electro-mechanical properties of the VCM systems can be modeled as $K_v/J$. Angular acceleration ($\alpha$) is the model output of the mechanics of the VCM systems. Finally, the angular position ($\theta$) of the VCM can be obtained by double integration of the angular acceleration.

5) Current Profiles in VCM Seek Operation

In a disk drive actuator, seek time is related to current profiles applied to the VCM. The fastest seek
times can be achieved with a bang-bang type of current profile. Figure 5 shows such a profile.

![Bang-Bang Seek Current Profile](image)

**Figure 5: Bang-Bang Seek Profile**

However, such a profile generates excessive acoustic noise. Since fast transitions contain frequencies which can excite resonances, settling times with this type of profile will be longer compared to other profiles.

For a saturated bang bang control input voltage, the equivalent bang bang current profile may not be generated due to back EMF voltage drop. The above example should be treated as a case study to illustrate the concept of thermal rise.

A sinusoidal current profile, as shown in figure 6, will result in a quieter drive. This type of current profile has the additional benefits of faster settling times and generates less heat compared to the bang-bang current profile. However, the disadvantage of such a current profile is slower seek times compared to a bang-bang system.

![Sinusoidal Seek Current Profile](image)

**Figure 6: Sinusoidal Seek Current Profile**

Therefore, servo engineers try to optimize all the above requirements in selecting a current profile. Usually, such a profile is a compromise between the bang-bang and the sinusoidal profiles. Figure 7 shows a typical optimized current seek profile that is commonly used in disk drive servo systems.

![Optimized Seek Current Profile](image)

**Figure 7: Optimized Seek Current Profile**

Please note that in all 3 cases the peak current is held constant since the maximum available current depends on the power driver.
The thermal rise and thermal resistance [1] related to the current profiles will be investigated in the following sections.

All three profiles were adjusted so that VCM will move the same distance after completing 1 cycle of each seek profiles. In addition, settling time is added to each profile to simulate the full seek time usually known as “read access time”.

6) Thermal Rise Prediction Simulations

Power profiles of a VCM coil can be calculated by taking the square of current profile and multiplying by its coil winding resistance. For the bang-bang current profile, the corresponding power profile is shown in figure 8.

\[
R_c(t) = \frac{\Delta T(t)}{P(t)}
\]  
(6)

Figure 9-10 show the power profiles corresponding to the sinusoidal and optimal seek current profiles. Where,

\[R_c(t)\] = Thermal Resistance (°C/W) of VCM coil as a function of time

\[\Delta T(t)\] = Change of Temperature (°C) of VCM coil as a function of time
\[ P(t) = \text{Current generated power (W) as function of time} \]

Detailed discussions of thermal resistance of VCM coil can be found in [1].

The power profiles as shown in figure 8-10 can be used in calculating the change of temperature of the VCM coil. They are calculated from the following equation:

\[ \Delta T(t) = P(t) \times R_s(t) = i(t)^2 R_w \times R_s(t) \quad (7) \]

Where,

\[ i(t) = \text{Current Profile input to VCM coil (mA)} \]
\[ R_w = \text{VCM coil coil winding resistance (\Omega)} \]

A thermal rise profile of VCM within a drive is experimentally collected at a fixed DC power level. Figure 11 shows such a profile.

\[ R_s(t) = \sum_{k=1}^{6} R_s \left( 1 - e^{-t/\tau_k} \right) \quad (8) \]

Where,

\[ R_s, \tau_k = \text{Curve fitting parameters} \]

By using equation (7) and (8), thermal rise within the coil after completing 1 cycle of seek profile is calculated. Figures 12-14 show the thermal rise within a VCM generated by bang-bang, sinusoidal and optimized seek profiles for 10 seek cycles, respectively.

![Figure 11: Thermal Rise of VCM coil](image)

Through a curve fitting technique a sixth order model is derived and used in the simulation program:
The VCM coil temperature can be calculated by running the thermal rise simulation consecutively. The effects of different ambient temperature can also be simulated in this program. Figures 15-17 show the thermal rise with an ambient temperature of 55 °C after 20,000 continuous seeks with bang-bang, sinusoidal and optimized seek current profiles respectively.
Figure 17: Thermal Rise of VCM Coil with Optimized Seek Current Profile for 20000 Seek Cycles

The thermal rise of VCM coil generated in figures 15-17 with different seek current profiles can be examined. It can be seen that the bang-bang seek current profile generates the most heat (maximum temperature reaching 143.6°C) while the sinusoidal current profile generates the least amount. (maximum temperature reaching 95.4°C).

In disk drive application, dwell time is usually added to simulate thermal rise in VCM coil accurately. Dwell time is the average wait time between seeks. For a spindle motor with rotational speed of 5400 rpm, dwell times of 4.167 ms (half a revolution) and 8.333 ms (full revolution) are usually used.

Figure 18 shows the different seek current profiles with a dwell time of 4.167ms added at the end of the seek profiles.

Figure 18: Seek Current Profiles with 4.167 ms Dwell Time

Figures 19 and 20 show the thermal rise plots with the bang-bang current profile when 4.167 ms and 8.333 ms of dwell time are added correspondingly.

Figure 19: Thermal Rise of VCM Coil with Bang-Bang Seek Current Profile with 4.167 ms Dwell Time
From the above figures, the highest temperatures reached by the VCM coil with a bang-bang seek current profile with 4.167ms and with 8.333ms dwell times are 112.8 °C and 97.7 °C respectively. In both cases these are lower than the no-dwell condition (143.6 °C). It can be seen that dwell time is beneficial in alleviating the temperature rise of VCM coil during seek operations.

7) An Innovative Approach Utilizing VCM as a Thermal Sensor

After running thermal rise simulations, if the highest temperature reached within the VCM coil is beyond an acceptable level, then thermal rise within the VCM should be monitored. When the temperature reaches a certain level, seek operations may be slowed down to prevent damage to the coil and the drive. Obviously, a reliable and “no cost” sensing approach is the preferred method.

This section introduces an innovative approach to sensing the VCM coil temperature by utilizing the coil performance. This approach is a non-intrusive measurement method.

As discussed in an accompanying paper [1], the coil resistance increases with temperature. The resistance of a heated coil can be calculated from the relation:

$$ R_f = R_i (1 + \xi \Delta T) $$

where,

- $ R_f $ = VCM coil resistance at time $ f $ (Ω)
- $ R_i $ = VCM coil resistance at time $ i $ (Ω)
- $ \xi $ = Coefficient of thermal sensitivity ($ ^{°}C $)
- $ \Delta T $ = Change in temperature from time $ i $ to time $ f $ ($ ^{°}C $)

For VCM coils whose coil resistance has increased due to higher temperatures, less current will flow at a given level of input voltage. Table 1 shows copper coil winding resistance value changes with different temperatures from its initial value of 14.2 Ω. The corresponding current levels to each resistance value for a fixed input voltage level of 8V is also tabulated.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>VCM Coil Resistance (Ω)</th>
<th>Current (mA @ 8V)</th>
<th>% change in Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>14.2</td>
<td>563.4</td>
<td>0%</td>
</tr>
<tr>
<td>35</td>
<td>14.8</td>
<td>542.2</td>
<td>-4%</td>
</tr>
<tr>
<td>45</td>
<td>15.3</td>
<td>522.6</td>
<td>-7%</td>
</tr>
<tr>
<td>55</td>
<td>15.9</td>
<td>504.4</td>
<td>-10%</td>
</tr>
<tr>
<td>65</td>
<td>16.4</td>
<td>487.4</td>
<td>-13%</td>
</tr>
<tr>
<td>75</td>
<td>17.0</td>
<td>471.4</td>
<td>-16%</td>
</tr>
<tr>
<td>85</td>
<td>17.5</td>
<td>456.5</td>
<td>-19%</td>
</tr>
<tr>
<td>95</td>
<td>18.1</td>
<td>442.6</td>
<td>-21%</td>
</tr>
</tbody>
</table>

Table 1: Change in coil resistance with respect to Temp at a DC supply voltage of 8V
The torque constant \((K_t)\) within VCM operational range will also be affected by temperature. It is inversely proportional to temperature increase. \(K_t\) variation with temperature can be expressed as:

\[
K_{t,f} = K_{t,i} \left(1 + \xi_{K_t} \Delta T\right)
\]

(10)

where,

\[K_{t,f} = K_t \text{ at time } f \text{ (gmf-cm/A)}\]

\[K_{t,i} = K_t \text{ at time } i \text{ (gmf-cm/A)}\]

\[\xi_{K_t} = \text{Coefficient of thermal sensitivity for } K_t \quad \text{(^oC)}\]

Within the VCM operating temperature, the coefficient of thermal resistance for \(K_t\) is \(-0.00139/^oC\). Table 2 shows the tabulated values of \(K_t\) at different operating temperatures. The nominal \(K_t\) value is equal to 980 gmf-cm/A at 25\(^o\)C.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>(K_t) (gmf-cm/A)</th>
<th>% change in (K_t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>980.0</td>
<td>0%</td>
</tr>
<tr>
<td>35</td>
<td>966.4</td>
<td>-1%</td>
</tr>
<tr>
<td>45</td>
<td>952.8</td>
<td>-3%</td>
</tr>
<tr>
<td>55</td>
<td>939.1</td>
<td>-4%</td>
</tr>
<tr>
<td>65</td>
<td>926.5</td>
<td>-6%</td>
</tr>
<tr>
<td>75</td>
<td>911.9</td>
<td>-7%</td>
</tr>
<tr>
<td>85</td>
<td>898.3</td>
<td>-8%</td>
</tr>
<tr>
<td>95</td>
<td>884.6</td>
<td>-10%</td>
</tr>
</tbody>
</table>

Table 2: Change in \(K_t\), wrt Temperatures

The reduction in VCM coil current and \(K_t\) due to higher temperatures will result in a reduction in acceleration of the VCM actuator. Assuming \(J\) equals 41.5 gm-cm\(^2\), table 3 shows the VCM acceleration and its percentage change at different temperature levels, for a fixed saturated voltage input of 8V.

<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>(K_t) (gmf-cm/A)</th>
<th>Current (mA)</th>
<th>(K_t/J) (rad/sec(^2))</th>
<th>% change in ang. Accel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>980.0</td>
<td>563.4</td>
<td>13.3</td>
<td>0%</td>
</tr>
<tr>
<td>35</td>
<td>966.4</td>
<td>542.2</td>
<td>12.8</td>
<td>-5%</td>
</tr>
<tr>
<td>45</td>
<td>952.8</td>
<td>522.6</td>
<td>12.0</td>
<td>-10%</td>
</tr>
<tr>
<td>55</td>
<td>939.1</td>
<td>504.4</td>
<td>11.4</td>
<td>-14%</td>
</tr>
<tr>
<td>65</td>
<td>926.5</td>
<td>487.4</td>
<td>10.9</td>
<td>-18%</td>
</tr>
<tr>
<td>75</td>
<td>911.9</td>
<td>471.4</td>
<td>10.4</td>
<td>-22%</td>
</tr>
<tr>
<td>85</td>
<td>898.3</td>
<td>456.5</td>
<td>9.9</td>
<td>-28%</td>
</tr>
<tr>
<td>95</td>
<td>884.6</td>
<td>442.6</td>
<td>9.4</td>
<td>-29%</td>
</tr>
</tbody>
</table>

Table 3: Change in acceleration with respect to temperature

As shown in table 3, at higher temperatures, acceleration of the VCM will be lower. Thus, the distance traveled by the VCM during a particular interval will be less at higher temperatures than at room temperature. The distances traveled at different temperatures can be compared and a calibration table can be made.

While operating, distance traveled by the VCM can be monitored for saturated voltages. A reduction in traveled distance for a fixed interval is an indication of increased VCM coil temperature. Seeks may be slowed down to prevent coil damage. Thus, the coil performance could be used as a temperature sensing mechanism to monitor VCM temperature.

Angular acceleration (\(\alpha\)) of VCM actuator is directly proportional to \(K_t\) and current, and inversely proportional to inertia (\(J\)). The relation can be expressed as:

\[
\alpha = \frac{K_t}{J} \cdot i
\]

(11)
8) Simulation Results

Three curves of traveled distance at different temperatures are shown in Figure 21. One of the curves represents number of tracks traveled by the VCM actuator over a period of time. The coil resistance \( R_C \) at 25\(^\circ\)C is 14.2Ω and \( K_t \) is 13.6 oz-in/A (980 gmf-cm/A).

The second curve represents the tracks traveled by the actuator at 55\(^\circ\)C. At this temperature the value of \( R_C \) is 15.9Ω and \( K_t \) is 13.0 oz-in/A (939.1 gmf-cm/A).

The third curve represents the tracks traveled by the actuator at 85\(^\circ\)C. At this temperature the value of \( R_C \) is 17.5Ω and \( K_t \) is 12.5 oz-in/A (898.3 gmf-cm/A).

![Figure 21: Simulated Results: Distance traveled by VCM actuator at different temperatures](image)

The results show that the distance traveled at different temperatures is reduced with increased temperature. At higher temperatures, the acceleration capability of the VCM system decreases. This can be best observed by measuring the distance traveled at selected servo wedges. Since the spindle rotates at a fixed speed, servo wedges which are spaced from each other with fixed distances can be used as timing indicators.

Figure 23 shows the distance traveled during a fixed interval of time (i.e., a certain servo wedge) at different operating temperatures. Figure 24 is obtained by normalizing traveled distance drop during different time intervals to a traveled distance percentage drop at 25\(^\circ\)C. One can see that the time interval to make the final measurement is not a critical factor in measuring the thermal rise in a coil. As can be observed, the percentage drop of traveled distance is almost the same even if measurements are taken at different time intervals (which were after 20, 25, 30 and 35 wedges).
10) Conclusions

In this paper, a simulation program to predict the thermal rise of VCM coils for different seek current profiles was presented. The program could be used to calculate the thermal rise by using the measured thermal resistance of the coil for different seek current profiles.

In the second part of the paper, an innovative approach to indirect VCM coil temperature measurement technique is described. This approach does not require the use of a temperature sensor. With this technique the temperature of the coil could be monitored throughout its operation. Experimental results were shown to verify the concept.

11) Acknowledgement

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12) References
