Modeling and Characterization of Magnetic Head's Areal Density

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Abstract: The biggest challenge of any hard disk drive (HDD) company is increasing the Areal Density Capability (ADC) which indicates how much information can be stored in a hard disk drive. Thus, many companies are trying to optimize multiple settings to increase the Areal Density. To determine whether a magnetic head can provide higher ADC, characterization and modeling are needed. This paper modeled the ADC and understand how multiple environments, namely Position Error Signal (PES), Head-Media Spacing (HMS), and Bit Per Inch (BPI), affect the magnetic head's Symbol Error Rate (SER) and Magnetic Core Width (MCW). The ADC can be modeled as a function of SER and MCW. A python code was written to process all the data of obtained from experimental testing to show the sensitivity of each environment on a specific magnetic head. Once the environment sensitivity is ready results showed the ADC behavior for each environment as three-dimensional. Also, the maximum Bit Per Inch (BPI) and Track Per Inch (TPI) were computed to determine the maximum possible ADC of the magnetic head. The result showed a 3-dimensional ADC of a magnetic head with different environmental conditions with a peak of ~1300 Gbit/in^2 and max TPI of ~850 KTracks/in at a PES track% of 6.2 with an HMS value of 0.4 nm. It also corresponds to the smallest max BPI with a value of ~1510 Kbits/in. It was concluded that decreasing the HMS at a PES track of 6.2% would increase the ADC.

Key Words: Areal Density Capability; Head-Media Spacing; Position Error Signal; Off-Track Read Capability; Bit Aspect Ratio

1. INTRODUCTION

With the massive amount of data being produced, increasing storage capacities of hard disks is needed. The capacity depends on the areal density capability (ADC) of hard disks. It tells us how much information can be stored in a hard disk drive. This ADC is a key metric for magnetic recording systems which has increased over 10^8 times during the last 60 years (Chen & Huo, 2018). The way to achieve a higher areal density is by introducing new technology like Microwave-Assisted Magnetic Recording (MAMR) a next generation perpendicular magnetic recording (PMR). This technology can provide up to 4 Tb/ in^2. The main component in this technology is the spin torque oscillator (STO) (Katayama et al., 2014). The STO is an external component that helps in reducing the coercivity of the disk which makes the disk easy to write even using a very narrow writer. There are existing technologies called two-dimensional magnetic recording (TDMR) and shingled magnetic recording (SMR). Sann (2014) shows that this technology has been introduced in the HDD industry to improve the areal density further until new technology called heat assisted magnetic recording (HAMR), microwave-assisted magnetic recording (MAMR), and bit patterned media recording (BPMR) are mature enough. The SMR technology method overlaps wide tracks to make the track narrower, while TDMR is a reader technology that helps read narrower tracks.

The critical difference between these technologies is the different ways to squeeze more information further while making the track readable. Squeezing more information will eventually make the SER poorer but can still be accepted at specific criteria. This will eventually increase the areal density. Figure 1 shows the crucial difference between each technology.

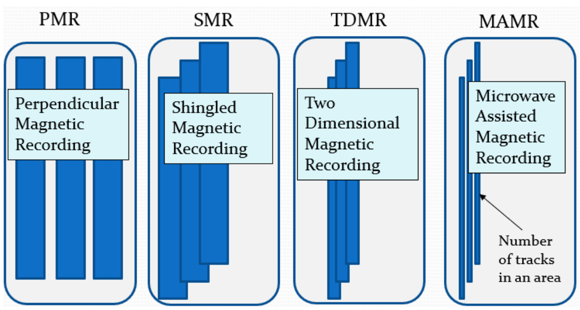

Fig. 1. The Development of Magnetic Recording Technology

Another method to further increase the areal density is by scaling. Taratorin (2004) mentioned scaling was used several years ago to further increase areal density. These methods are adjusting the HMS, dimension of the magnetic head and reducing the grain size. The bit per inch (BPI) can also play a role in ADC. As the BPI increase, the off track read capability (OTC) monotonically decreases because of a decrease in signal-to-noise ratio (SNR) (Chen & Huo, 2018). When the OTC decreases, the SER degrades (Taratorin, 2004, p.85). The position error signal (PES) can also provide some variations in the SER which eventually leads to variations in the ADC (Reaño, 2016).

This study aims to model the ADC of a magnetic head with a given environmental condition: HMS, BPI, and PES. Other variables are the symbol error rate (SER), magnetic core width (MCW), off-track read capability (OTC), and track pitch per inch (TPI). These inputs can produce a multiple 3D ADC Curve that determines the behavior of the magnetic head at any given environmental condition.

Areal density can be calculated using equation 1, while the Bit Aspect Ratio can be calculated using equation 2. This equation was used to get the maximum TPI and BPI possible to reach maximum ADC Gain with a specific Bit Aspect Ratio (Chen & Huo, 2018).

$$ADC = BPI * TPI \qquad \text{(Eq. 1)}$$

where:

ADC = Areal Density Capability (Gbits / in^2)
BPI = Bit Per Inch (Bits / in)
TPI = Track Per Inch (Tracks / in)

$$BAR = BPI / TPI \qquad \text{(Eq. 2)}$$

where:

BAR = Bit Aspect Ratio (Bits / Track)
BPI = Bit Per Inch (Bits / in)
TPI = Track Per Inch (Tracks / in)

2. METHODOLOGY

2.1 Data Preparation:

It is required to prepare the necessary information. All this information is based on data during the experiment of Western Digital. A python code is used to process all the raw information into a simple sensitivity trend for each condition. This information sets the environment used to generate the ADC Curve of a specific head. Four pieces of information are required to begin the simulation which is obtained from experimental testing by sampling through the following quantities: HMS Trend, PES Response, KBPI Response, and OTC Sensitivity.

The HMS Trend shows the SER or MCW as a function of change in HMS. The model creates a sensitivity trend that shows how much difference in SER / MCW is seen by changing the HMS. Table 1 is sample data of the HMS trend for different slider serial numbers (Slider SN) of those different heads. The experiment tested 2322 magnetic heads per HMS to make it more reliable. The HMS trend shows the distance between the Head and Disk. The SER and MCW are the raw values from population data with different HMS. This information indicates how a magnetic head's performance is affected as it moves further or closer to the disk. The performance of the head gets better as we move closer to the disk, but media separation is only several nanometers and can no longer be significantly reduced (Taratorin, 2004). The code is responsible for providing the trend. This is considered one of the environments.

Table 1. HMS Trend Sample Data

Slider SN	MCW	SER	HMS
49E6319838	56.1	-2.26	0.6
49E633B51B	51.1	-2.06	0.8
49E6317508	51.1	-1.86	1.2

The PES Responses indicate how much in terms SER / MCW of the magnetic head is experiencing more reader variations at the center track. The SER / MCW can be poorer if the reader variation is too high (Reaño, 2016). This is another environment that has been considered. Table 2 shows the sample data that is needed. The experiment used 6388 samples tested on 10 testers. Table 2 is a sample of a few magnetic heads per tester.

Table 2. PES Response Sample Data

Slider SN	Tester	PES	MCW	SER
49E631760D	B1	8.55	69.9	-2.57
49E6319838	B2	8.11	56.1	-2.26
49E632B802	B2	8.35	50.2	-2.01

The KBPI Response shows the change in SER / MCW as KBPI increases. The KBPI trend is defined as how many bits can be stored on one track. The model created a trend that shows the SER / MCW as a function of BPI which is an important factor for the OTC Generator. Table 3 is sample data that shows the KBPI Response. In this experiment, 124 pcs of the magnetic head were tested at different KBPI or frequencies.

Table 3. KBPI Response Sample Data

Slider SN	SER	MCW	KBPI
4BC590AB34	-2.14	55.4	1826
4BC590B121	-1.85	55.3	1926
4BC590B712	-1.38	60.4	2126

The OTC trend provides the reader's sensitivity of the magnetic head as it goes further away from the center of the track. The OTC tells how far the magnetic head can go before the SER degrades to a certain threshold. The SER degrade because it is now reading old information (Taratorin, 2004, p.85). Further squeezing more tracks is also another reason why OTC is getting lower because the track width is getting lower. Table 4 is sample data on how far can the magnetic head go before the information is hard to read. Table 4 also shows that if the reader moves so far from the center of the track, the SER can be so poor that it can no longer do measurements. The reason is the reader is reading unwanted information between the desired tracks. In this experiment, two magnetic heads were used to get this information.

Table 4. OTC Sensitivity Sample Data

Slider	OTC	SER	MCW
1	35	-3.5	52
1	55	-	52
2	35	-1	40
2	55	-	40

2.2 Prepare the Environment:

Once all the data have been read and processed, one can determine the environmental condition used in getting the track pitch by OTC generator. There are four conditions that the code can show: the Head-Media Spacing, Position Error Signal, KBPI, and the OTC. From these data, a sensitivity analysis was performed to develop the OTC generator which calculated the baseline SER / MCW. Once the new SER / MCW baseline has been calculated based on the type of environment including the KTPI or Track pitch.

2.3 Generate the OTC Profile per Environment:

Since the three environmental conditions have already been prepared, the code generates the OTC Profile. It started by getting the processed information from the OTC Sensitivity data and was used in the generation. The information shows the reader's sensitivity as it moves away from the center. As mentioned earlier, the SER degrades as it moves away from the reader because of unwanted information being read (Taratorin, 2004, p.85).

The generation of the OTC is a vital calculation to get the TPI or track pitch. It determines how much the SER can be degraded as the track pitch gets lower, it continues to lower it until it meets the acceptable SER based on OTC. This model predicted that the OTC degrade in a quadratic behavior. Figure 2 is an OTC vs. Track Pitch at 9 Environmental Condition (1 PES, 9 KBPI, 1 HMS). Once the profile has been set, the code started to get the 9 values of KTPI or Track Pitch on which the SER is close to the SER Threshold. This information was used in the following process.

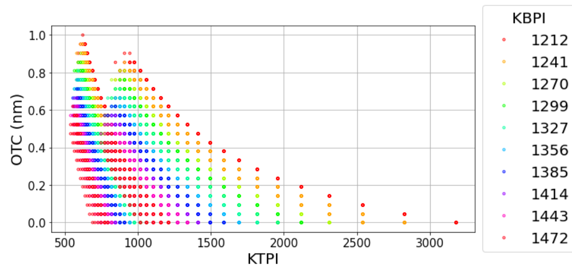

Fig. 2. OTC at Different KTPI / Track Pitch

2.4 Compute for the ADC / BAR:

The ADC is just the product of the BPI and TPI, and the BAR is the ratio of BPI over TPI. Once the information of the BPI has been proceed and the TPI has been computed in the previous process, we computed for the ADC and Bar. Figure 3 shows the response of the ADC vs. Bar at different Environmental conditions (5 KBPI, multiple HMS, 1 PES). By adding multiple PES environments, we were able to produce a 3-D plot as shown in figure 3.

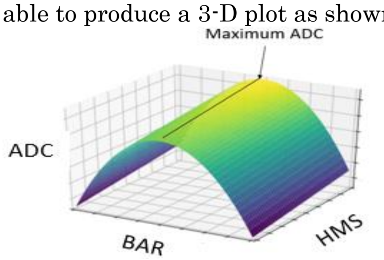

Fig. 3. ADC vs. Bar at different HMS

2.5 Compute for the Maximum ADC:

Since the code generated the profile for ADC as a BAR function per environment, the maximum ADC possible per environment by using maxima and minima was computed. Since it has multiple environmental conditions, the code generated a list of maximum ADC per environmental condition. An example can be seen in figure 3.

2.6 Compute for the Maximum ADC:

The final computation calculates the maximum TPI and BPI that must be used to meet the maximum ADC. This has been recomputed for each condition. Since the code knows that the ADC is a product of BPI and TPI and the BAR is the ratio of BPI over TPI, the TPI and BPI were just recomputed since the Max ADC at a specific BAR is already known.

3. RESULTS AND DISCUSSION

3.1 Sensitivity Profile:

The model has generated a sensitivity profile that shows how the magnetic head behaves in 3 different types of environments. The sensitivity used in this model is based on a quadratic equation. The trend may vary depending on the magnetic head design and the sample size provided.

By looking at the behavior of the head at different HMS, it shows the SER degrades as it moves further from the disk while MCW can be lower because the writer is far from the disk shown in Figures 4 and 5, respectively.

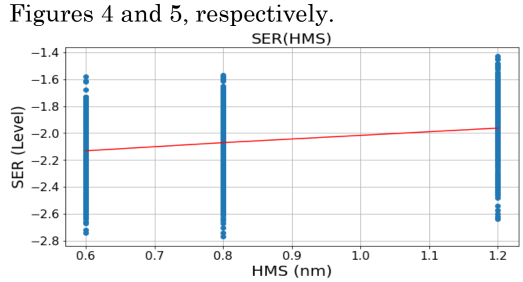

Fig. 4. SER as a function of HMS

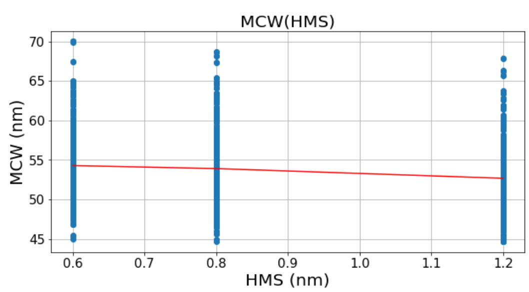

Fig. 5. MCW as a function of HMS

Figure 6 shows that the SER becomes poorer because the bits being read are very small, making it harder to read, while the MCW becomes bigger at a higher frequency in figure 7.

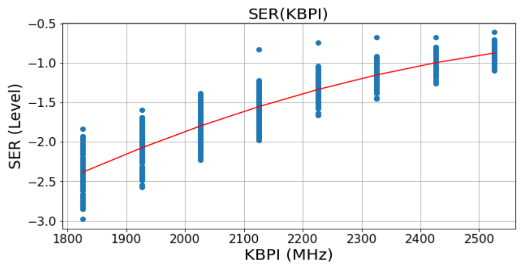

Fig. 6. SER as a function of KBPI

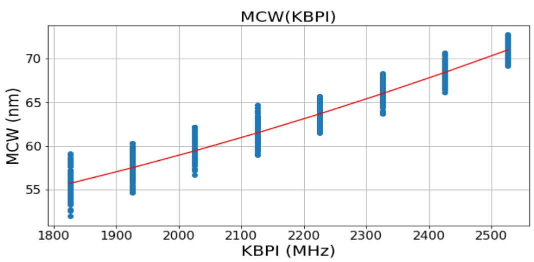

Fig. 7. MCW as a function of KBPI

Figure 8 shows the SER, and Figure 9 shows the MCW as a function of PES. As mentioned earlier, the PES varies between testers only. The data is using population data with multiple tester that have different PES Responses. It is wise to also consider the PES variations between testers.

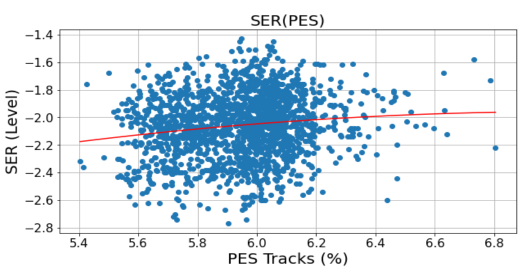

Fig. 8. SER as a function of PES

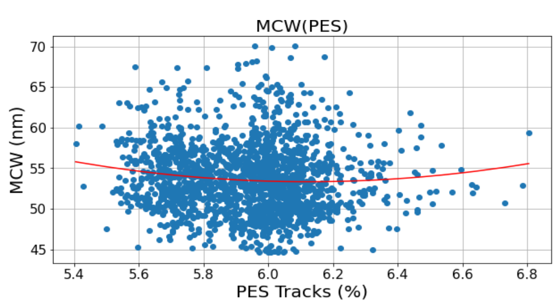

Fig. 9. MCW as a function of PES

Figure 10 below shows how far the magnetic head can go as it moves further from the disk. This is essentially sensitivity data to get the best track pitch possible before our data is unreadable.

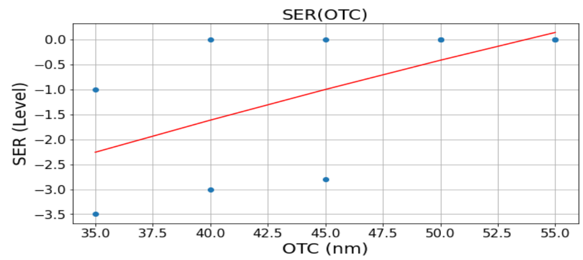

Fig. 10. SER as a function of OTC

3.2 ADC vs. BAR Profile:

The model has generated a 3D contour plot based on ADC vs. BAR vs. PES per HMS, as shown in figure 11. It has used the inputted BPI and calculated TPI to get the ADC and BAR per environment. The model can show how much impact each setting provides to the data storage with this information. It is important to remember that the KBPI is already part of the ADC and BAR. Figure 11 shows the ADC gets lower as the HMS keeps increasing. The main reason for this behavior is the SER gets poorer at higher HMS. Poor SER indicates that the head can no longer squeeze more tracks. This results in lower ADC. SER also shows how well the head is reading and writing the information. Higher SER can also show that the head can squeeze more track on the disk. Even if the SER gets poorer as it keeps squeezing more tracks, it is still acceptable provided that the main track still has an acceptable SER value. The PES is not showing much impact based on the data generated.

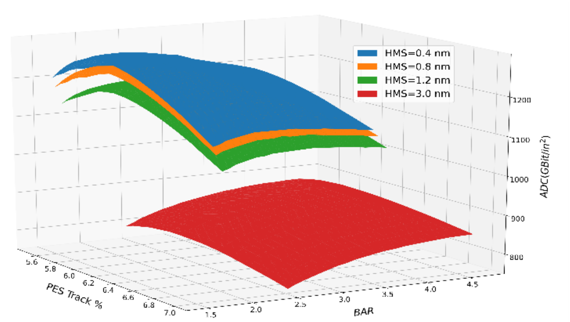

Fig. 11. ADC vs. BAR vs. PES per HMS

Since the ADC vs. BAR profile has been made, we computed for the maximum ADC at a specific BAR followed by BPI and TPI for this max ADC per environmental condition. Figure 12 shows the result. The maximum BPI and TPI are essential parameters determining how much ADC the magnetic head can provide. The max ADC of ~1300 Gbit/in^2 and max TPI of ~850 KTracks/in are found to be at a PES track% of 6.2 with an HMS value of 0.4 nm. It also corresponds to the smallest max BPI with a value of ~1510 Kbits/in.

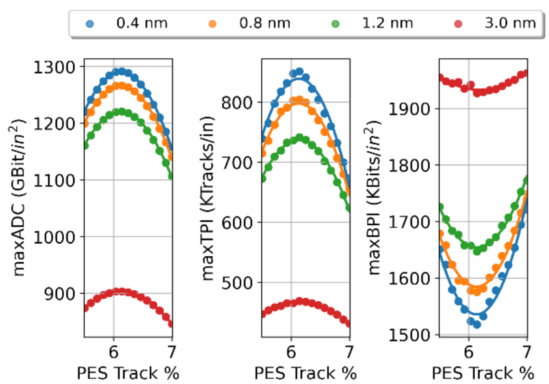

Fig. 12. Max ADC / TPI / BPI per environment

4. CONCLUSIONS

This model for understanding the areal density at the different environments of the magnetic head can be beneficial in quickly understanding how magnetic recording works. This model also shows how multiple environments, namely Position Error Signal (PES), Head-Media Spacing (HMS), and Bit Per Inch (BPI), affect the magnetic head's Symbol Error Rate (SER) and Magnetic Core Width (MCW). Once the SER and MCW of the magnetic head change, the ADC will also be impacted since it is a function of SER and MCW. The SER is an indication of how readable the information on a track is. The MCW is an indication of how wide the track will be. These two are major parameters on ADC because they defined how much information can be squeezed while still making it readable. The HMS shows more ADC value as it decreases because SER is getting a lot better. Since the SER is better, it is an indication that more tracks can be squeezed. The risk of further reducing HMS is the head might hit the disk which will cause destruction.

The BAR shows high ADC at a certain value. Since BAR is a function of BPI and TPI, there will be a certain BAR value that will achieve a high ADC. This model helps in determining that value. By maintaining a PES track of 6.2%, at a spacing of 0.4 nm, one can obtain the max ADC. Decreasing the spacing would be a technological challenge to further increase the max ADC. These environments can be a major contributor to ADC because it mainly affects the SER and MCW of the magnetic head Given this model, one can study the different environmental conditions to understand how one specific situation can change the amount of data storage.

5. ACKNOWLEDGMENTS

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