ABSTRACT
To sustain market shares in the highly competitive data storage industries, continual improvements in servo performance of Hard Disk Drives (HDDs) are essential. With tight scheduling of the servo-mechanical design and evaluation cycle, an efficient integrative simulation platform is needed to evaluate and conduct fast verification of target specifications. In this paper, we propose a simulation platform for modelling, simulation, and control of next generation of ultra-high storage density HDDs. A case study is conducted to predict the achievable track density with appropriate Bit Aspect Ratios (BARs) for 4 Tb/in² areal density. Our simulation results show the effectiveness of the proposed simulation platform in efficient estimation of the achievable tracking performance and achievable Track-Per-Inch (TPI) to support next generation of magnetic recording technologies.

INTRODUCTION
With the vast amount of information we carry with us everyday, HDDs have become indispensable tools for data storage in many domestic and industrial electronic products. The first HDD was built in 1956 with a mere capacity of 5 MB. After more than fifty years of continuous research efforts on improved magnetic recording technologies, the latest 3.5” HDD has a data storage capacity of 3 TB; more than 600,000 times! The storage capacity of HDDs continues to grow at a rate of 40% per year with reduced form factors. Today, HDDs remain as the cheapest form of non-volatile data storage devices and upcoming promising technologies like Bit-Patterned Magnetic Recording (BPMR), Heat-Assisted Magnetic Recording (HAMR), etc., are proposed to further increase HDDs’ storage capacities to satisfy consumers’ needs.

This continuous requirement for higher storage density motivates us to develop a simulation platform for extensive realistic simulations of next generation ultra-high density HDDs beyond 1 Tb/in² storage capacity. The developed simulation toolkit [1] serves as a system-level input/output model for the simulation, evaluation and observation of servo patterns, Position Error Signal (PES) quality, as well as servo control performance, particularly for patterned media technology. Based on the developed platform for patterned media technology, a simulation case study is conducted using projection on a commercial drive to predict the achievable TPI, appropriate BAR and the gap needed to fill for 4 Tb/in² areal density.

HARD DISK DRIVE
To achieve the continued improvement and high degree of accuracy critical for high data track density, improvements in the servo system are of paramount importance. The head-positioning servomechanism in a HDD provides a means for locating Read/Write (R/W) heads in fixed radial locations over the disk surface and allowing the repositioning of these heads from one radial location to another in minimum time. There are typically three main servo control modes, namely track-seeking, track-settling, and track-following modes [2]. In this paper, the focus will be on the track-following operation to meet the ultimate objective of achieving high track densities which corresponds directly to high data storage capacities.

SERVO SIGNAL AND CONTROL LOOP SYSTEM
A typical HDD servo control loop is illustrated in Fig. 1. The servo signal generation and PES demodulation process are added in the loop to simulate the effects of media, electronics, and demodulation noise which will be lumped together as the PES sensing noise. The details of the simulation platform are discussed in [1].

Currently, most HDDs consist of a single actuator, the Voice Coil Motor (VCM), for positioning of the R/W head. In recent years, a secondary actuator or PZT micro-actuator is
appended piggy-back onto the VCM for improvement in R/W head positioning. A picture of a commercial dual-stage HDD is shown in Fig. 2, and the frequency response of the VCM is shown in Fig. 3.

**CONFIGURATION AND SIMULATION OF SENSING NOISE FROM PATTERNED SERVO**

For conventional continuous media recording systems, the BAR is usually around 6 to 8. However, in BPMR, a smaller BAR is preferred due to manufacturing limitations on the smallest lithography imprinting feature size. The BAR is targeted to be around 2 to 4. The same configuration was used in [1], where a BAR of 3.4 was chosen in the servo pattern model for projection of 1 Tb/in² areal density and 540 kTPI track density.

A typical ABCD servo pattern containing sixteen magnetic islands with alternating positive and negative magnetization is assumed fabricated on the patterned media with 220 servo wedges based on the conventional drive model. Thus, 220 sets of ABCD servo pattern layouts are generated and simulated with the assumption of 5% variation for position jittering, size fluctuation, and roughness defects encountered during the BPMR fabrication process for 1 Tb/in² density evaluation. Our simulation is conducted without disturbances, and a 3σ sensing noise value is found to be about 5.6% of the track pitch.

**DISTURBANCE MODELLING**

The plant model and the disturbance models are extracted from a commercial 3.5" 7200 rpm drive with track density of 145 kTPI. The Non-Repeatable Run-Out (NRRO) disturbances are obtained from the PES measured from the same 3.5" commercial drive, while the raw NRRO spectrum is then calculated by dividing the closed-loop NRRO spectrum by the magnitude of the sensitivity transfer function. The disturbances are then modelled and lumped together at the PES output accordingly. It can be seen from Fig. 4 that a significant portion of energy is heavily distributed at lower frequencies of less than 1 kHz where there are no resonant modes. This is due to the torque disturbances acting on the Head-Gimbal Assembly (HGA), such as windage pressure, flex cable bias, pivot bearing friction, and other nonlinearities, etc.
In the frequency range of 1 to 3 kHz where the baseline spectrum is comparatively lower, a few peaks at 1146 Hz, 1614 Hz, 2082 Hz, and 2800 Hz due to disk vibration mode/runout (excited by disk flutter) are observed. The arm and suspension vibrations excited by, e.g., airflow or head-disk contact, lie in the high frequency range (>3 kHz), while the flat base-line disturbance is mainly caused by the electrical noise of the servo signal. In this paper, the RRO components are assumed to be fully compensated and not considered.

**SINGLE STAGE CONTROL SIMULATION**

The controllers are redesigned using $H_\infty$ loop shaping and compared with the original PID-type controllers used in the original drive. The original control design uses a PID controller with a series of notch filters centered at 8 kHz, 11 kHz, 16.7 kHz, and 19.6 kHz. The major resonant mode at 6.2 kHz is attenuated by a peak filter at 6.5 kHz [3], so that the second phase margin at 5.6 kHz is stable (>80°) [4]. By using the $H_\infty$ loop shaping method, the open loop system achieves the crossover frequency of 1.29 kHz with phase margin of 46° and gain margin of 8.35 dB at 3.73 kHz (not shown).

From Fig. 5, we can observe that the torque disturbances at frequency range <1 kHz has been attenuated drastically. The flutter disturbances in the frequency range of 1 to 3 kHz are slightly amplified due to the sensitivity “hump”—a frequency range where disturbances are amplified by servo loop instead of being attenuated, and the peaks at higher frequency range are retained. Compared to the original PID-type servo which yields a track density of 145 kTPI, the proposed $H_\infty$ loop shaping control technique used in this projection had achieved a track density of 210 kTPI.

**DUAL-STAGE CONTROL SIMULATION**

For a conventional VCM actuator, the natural frequency of the first resonant mode is at about 5 to 8 kHz. It is very difficult to push the open loop servo bandwidth higher than 5 kHz, even with increased sampling rates. As such, dual-stage actuation is required to achieve higher track densities. For our simulations, a slider-based micro-actuator proposed by Hirano et al. in [5] is assumed to be appended onto the VCM. The frequency response of the slider MEMS-based micro-actuator is shown in Fig. 6. From Fig. 6, a resonant mode at 21 kHz caused by slider’s rotational inertia and stiffness of silicon structure and PZT ceramic can be seen. This resonant frequency can be adjusted by modifying the silicon structure design. For this actuator, there are no other resonant modes up to 100 kHz with almost zero phase delay which makes it easy to control. As such, extremely high bandwidth servo control can be realized using this micro-actuator as a secondary actuator.
Fig. 8: Magnitude of sensitivity transfer functions of closed-loop system.

The sampling rate is increased to 70 kHz and the dual-stage controllers are redesigned in decoupled master-slave configuration, using the $H_\infty$ loop shaping method for the VCM and $H_\infty$ loop shaping with peak filters [3] for the secondary actuator. The open loop bandwidth can be pushed up to 7 kHz, while the phase margin is 95°and gain margin is 5.02 dB as shown in Fig. 7. The maximum magnitude of the sensitivity hump is 6.08 dB as shown in Fig. 8.

Fig. 9: Simulation of resultant PES with variation of sensing noise (with respect to track pitch @ 2000 kTPI).

CASE STUDY SIMULATION RESULTS

To study the achievable servo performance for the areal density of 4 Tb/in², proper scaling is necessary for the sensing noise with respect to the BAR. According to [6], PES measurement noise scales with the track pitch/island features size. For different cases of BAR, the 3σ value is set as 5.6% of track pitch for BPM and is then scaled down accordingly. For example, the 3σ sensing noise = $0.056 \times 25.4 \times 10^6 / 1000 \times 10^3 = 1.422 \text{ nm}$ for 5.6% of track pitch under 1000 kTPI.

<table>
<thead>
<tr>
<th>DESIGN CONDITIONS</th>
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<tr>
<td>BAR</td>
<td>Track Pitch (kTPI)</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>1414</td>
</tr>
<tr>
<td>3</td>
<td>1154</td>
</tr>
<tr>
<td>4</td>
<td>1000</td>
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Table I: Simulation Results for Various BAR

Four cases of BARs from 1 to 4 are conducted to achieve 4 Tb/in² shown in Table I. It is worth noting that targeted 3σ PES is at 10% of track pitch. With BAR≥2 (where the targeted track density is <1414 kTPI), the servo system is able to suppress the resultant 3σ PES to meet the design specifications. However, there is still a gap to be filled by other means in order to reach a BAR of 1. It is possible to push the track density to 1716 kTPI at 7 kHz servo bandwidth for the features sizes targeted at 2000 kTPI or BAR=1 as shown in Fig. 9.

CONCLUSIONS

In this paper, a 3.5” HDD using dual-stage MEMs-based secondary actuators and advanced controller designs have been studied. The new slider-based micro-actuator design has a resonant mode at 21 kHz, and our simulation results show that it is possible for the proposed servo-mechanical system to operate at a BAR of 2. Using the developed virtual simulation platform, we demonstrated its effectiveness in our case study on commercial HDDs employing BPMR technologies. More advanced modules can be developed and integrated to forecast the targetable deliverables if desired specifications are achieved, which will directly translate into huge cost savings for manufacturing industries. Our further works include studies of 2.5” HDDs, which are predicted to the target form factor of 4 Tb/in² recording density.

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REFERENCES