Hard Disk Drive Performance Degradation Susceptibility to Acoustics

White Paper Developed by
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Mission Critical Facilities, Data Centers, Technology Spaces
and Electronic Equipment

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Introduction

As perpendicular magnetic recording technology[1] has matured and areal density growth of heads and media improvements has slowed, hard disk drive (HDD) development teams have gained surface area and have increased capacity by adding disks within the same form factor. The additional space consumption usually comes at a cost to servo-mechanical design. Disks, base decks, top covers, and head stack assembly arms become thinner and limit the mechanical design options that otherwise provide robustness to external excitations that impact HDD performance.

Although the transition to using helium inside HDDs results in an environment with very low airflow disturbance to the head, the designs become more susceptible to external vibration, especially vibration caused by coupling with acoustic sources. Future technologies that provide for even greater data track densities will unlock higher capacities but add significant stress to a HDD servo system's capability to remain on-track during external excitation events because the data will be written to or retrieved from narrower tracks.

As HDD servo-mechanical development continues, it enables sustained HDD performance under a wide range of external vibration conditions to meet performance criteria up to a critical capacity point dependent on each HDD company's design and model. Because stresses to the HDD tracking and settling capability accompany capacity advances, design considerations for a computing system that houses HDDs must account for the following:

- Controlling vibration that structurally transmits through the host chassis from adjacent HDDs and air moving devices (AMDs), like fans or blowers
- Controlling acoustics transmitted from AMDs operating at high speeds
- Controlling acoustics generated from airflow eddies in turbulent flow
- Controlling transmission of external events to rack and chassis subject

The objective of this white paper is to educate the data center community of the risks to HDD throughput performance from acoustics created by AMDs running at high speeds to adequately cool components within the racks. The methods used to optimize data center total cost of ownership (TCO) need to include the system performance risk impacting customer applications.

1. Perpendicular recording technology is the latest phase of magnetic recording technology that achieves higher storage densities by aligning the poles of the magnetic elements, which represent bits, perpendicularly to the surface of the disk platter.

Four factors involved in the increased risk of system performance loss in data centers are the following:

- The increases in HDD capacity resulting in smaller data track width for head to target and leading to higher susceptibility to external sources of vibration.
- The decrease of distance between AMDs and HDDs results from increasing density of components that accompany evolving storage and server industry trends.
- Cooling to meet thermal needs of IT system components with increased power consumption likely requires higher speeds of AMDs.
- The trend toward higher data center temperatures to optimize TCO often means that increased airflow and faster speeds of AMDs are needed to maintain required component temperatures.

The combination of these factors presents an increased risk of performance loss with HDDs and thus, hidden cost to the operation of a data center. These are discussed in the following sections.

Hard Disk Drive Susceptibility to External Disturbances

The primary objective for a HDD developer is to provide the lowest dollar per terabyte ($/TB) storage while maintaining performance and reliability standards across a wide range of operating conditions. As perpendicular recording technology reaches maturity, areal density improvements from heads and media using conventional magnetic recording (CMR) to grow capacity have slowed. Recent capacity growth has been attained by adding disks within the same form factor, trading surface area for mechanical robustness and also changing the modal response.

HDD heads read and write data using concentric tracks of magnetic grains on the media. The servo system controls the position of the head relative to the center of the data track and moves to a radial position on the disk to write or read the data. Magnetic fields are emitted from the head to flip magnetic bits and write data onto tracks. If the center of the head strays too far from the center of the data track, the magnetic field can impact the orientation of magnetic bits on adjacent data tracks and corrupt those data.

Before the HDD writes or reads data to a track, the servo system measures the relative distance between the center of the data track and the center of the head. This distance must meet certain criteria before a write or read can start. To protect data on adjacent tracks, the servo system suspends the write process until the head returns to an acceptable range to the track center, and the system must wait for at least one revolution of the disk to attempt again to write. This time delay increases latency and results in system performance degradation.

The HDD servo system has limits for rejecting external disturbances. The current sets of technologies and mechanics allow for error rejection below 2 kHz, but disturbances from AMDs can input excitations up to 20 kHz. Future HDD capacity increases require technologies that increase stress to the servo-mechanical systems. Additionally, growth in surface area of more recent 3.5 inch form factor HDDs to maintain capacity growth to $/TB targets results in reduction of the mechanical system's capability to withstand external disturbances.

The relative motion between the head and the disk, called off-track motion, may be caused by internal and external disturbances. Internal disturbances include excitation from disk-driven airflow (windage) and settle dynamics. Windage interacts with the mechanical structure that holds the head. Settle dynamics result as mechanical system resonances excited by the servo system decelerate the head stack assembly. Helium-filled HDDs provide a low windage environment, and the windage disturbance is also low, so the HDD internal disturbance may be very low. Servo systems are optimized to limit excitation of known mechanics, so internal disturbances have become an even smaller component of off-track motion.

The largest modern risk factor for off-track motion is the coupling of the HDD with external disturbances associated with the chassis housing the HDD. AMDs, typically fans or blowers, used to cool components in the same chassis as that containing the HDDs are generally the source of external disturbances. AMDs generate three forms of disturbances: mechanical vibration, airflow turbulence, and acoustics. As their impellers spin, the AMDs shake at characteristics related to the number of motor poles and unbalance. The mechanical vibration may transmit through the chassis to the HDD. Generally, vibration amplitude tracks with the second power of air mover speed. Airflow is the purpose of the AMD, but turbulence may occur when airflow encounters narrow gaps near the HDD and shake the HDD. Acoustics is the other form of disturbance and has become a larger risk factor in loss of HDD performance over the past several years. Key characteristics of acoustics relevant in the discussion of HDD performance degradation are sound pressure level (unweighted, i.e., not A-weighted) and frequency content. Frequency content tracks linearly with speed, but sound pressure tracks with the fifth power of speed when the air mover is a fan.

Mechanisms Behind Disturbances to HDD Performance

Just as HDD manufacturers have been adding more disks to increase capacity, chassis designers have been increasing the number of HDDs in each enclosure. Additional HDDs tend to increase airflow restrictions in the system. Providing adequate airflow over the increased pressure drop means driving AMDs at higher speeds. Magnitudes and frequencies of external disturbances increase with air mover speeds. So as HDDs have become more sensitive to acoustic disturbance, the external disturbances have also become more problematic.

Structurally transmitted vibration was once the primary risk of external disturbance to the HDDs, but various techniques have propagated through the industry to surmount much of this risk, such as means of vibration isolating HDDs or AMDs from their host chassis. Acoustics has become an increasingly important factor in performance degradation. The sound field and sound sources must be carefully understood and controlled in the design of HDD storage enclosures. The convergence of technologies, properties, and mechanisms responsible for this effect is considered in the following.

AMDs generate acoustics in three principle ways. When the blade of an air mover passes a single point in space it generates a pressure pulse, and the train of pulses appears as harmonics of blade pass frequency, given by:

$$f_b = N_b \times \frac{\text{RPM}}{60\ \text{sec/min}}$$

where f_b is the blade pass frequency in Hz, N_b is the number of blades on the rotor, and RPM is the rotational speed of the rotor. Harmonics of blade pass will also be present because the passage of the blade is truly more like an impulse than a sinusoid. The primary purpose of an AMD is to move air, but the airflow itself interacts with several structures including the air mover itself. Acoustically the result is broadband noise that is a function of local airflow velocities, eddies, etc., but with no particular frequency components. Finally, airflow across and near the HDD can be turbulent and can result in low-frequency noise.

Empirical fan laws show that sound pressure level (SPL) varies with the fifth power of fan speed, or in logarithmic terms

$$\Delta \text{SPL}_1 \cong 50\log_{10}(\text{RPM}_1/\text{RPM}_2), \quad \text{dB}$$

For blowers, this is closer to ~70 × log(RPM_1/RPM_2) dB. This means that a small increase in AMDs speed can result in a large increase in sound pressure level. Because AMD speeds need to be higher to provide the cooling needs of ever-increasing power of components, e.g., central processing units (CPUs), memory, peripheral component interconnect (PCI) cards, etc., and to overcome chassis airflow impedance associated with increase of density of components in a chassis, sound pressure levels at HDDs have become higher than in the past.

Sound pressure level is only one aspect of the acoustics challenge. Frequency content must be equally considered. As HDDs increase in capacity and the track width size on the disk surface continues to decrease becomes smaller, the frequency range of impact to the HDD broadens. Present HDDs show sensitivity up to ~20 kHz. AMDs can have significant acoustical content up to that range, and vibration from blade-pass harmonics scale linearly with speed of the AMD. That means an increasing presence of higher frequency content as higher speed AMDs are used, and HDD servo systems struggle to reject that disturbance.

Increased system computing power and component density are becoming more common in modern computer and server design. These density changes result in AMDs that produce ever increasing sound pressure levels and frequency content that can affect HDD performance, which will need to be addressed by system designers. Because there are a myriad of AMDs (and resulting frequency characteristics) and chassis designs, there is no specific reference speed for an AMD that may be used to determine the HDD performance in an enclosure. Instead, the chassis designer must understand the acoustical frequency profile and amplitudes that must be met for the target HDDs. Measurements of HDD performance, e.g., throughput, alone will not suffice in identification of mechanisms that will help a host chassis designer to improve the design, although it can be used in correlation efforts to sound pressure level profiles as a function of frequency.

Several important characteristics related to external disturbance to HDDs can be seen in the typical server acoustical profiles shown in Figure 1. First, note the blade-pass harmonics indicated by the multiple spikes and the broadband content that spans between spikes. Also note that frequency content shifts linearly with fan speed and sound pressure levels at ~50 × $\log_{10}$(fan speed change) (blue solid vs. gray dashed lines). Furthermore, it can be seen that two different HDD slots may have quite different acoustical signatures, and thus, may require different chassis solutions (blue solid versus orange dotted curves). Finally, note that the acoustical hardware measurement method (microphone at rear of HDD) and fast Fourier transform (FFT) portrayal is just one of many ways to characterize the acoustical pattern that affects an HDD in the system. HDD models differ as to which frequency ranges they are sensitive to and whether blade-pass harmonics or broadband or both are more problematic.

HDD Servo-Mechanical Ability to Correct for Acoustical Disturbances

Acoustics from AMDs can create two issues. First, the excitation extends out to 20 kHz, whereas current servo capability to correct for excitation is up to

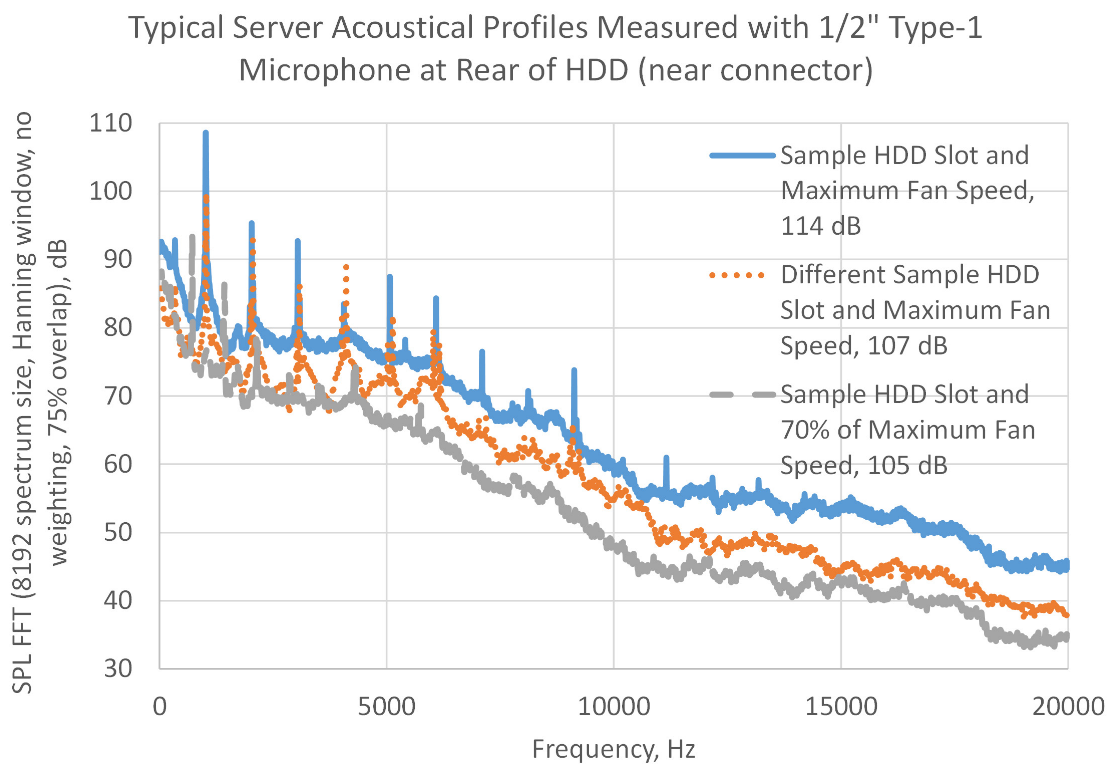

Figure 1 Typical server acoustical profiles highlight several important characteristics related to external disturbance to HDDs. FFT of the sound pressure level uses 8192 spectrum size with a Hanning Window, no weighting, and 75% overlap.

2 kHz. Second, the motion departs from rigid body in-plane motion, making it impossible for the piezoelectric rotational vibration sensors to measure the HDD motion. Successful rotational vibration (RV) feedforward systems measure the rigid body motion of the HDD using two piezoelectric sensors on the printed circuit board assembly (PCBA). These sensors only measure in-plane motion (i.e., linear motion in the *x*–*y* direction and rotational motion around the *z*-axis). They do not measure rotational motion around *x*-axis or *y*-axis or *z*-axis linear motion and cannot accurately measure nonrigid body motion. The servo system is therefore not optimized to compensate for motion driven by strong acoustical inputs into the drive system.

Empirical data can be the key to understanding the impact of acoustics on the HDD, such as measurements of input/output operations per second (IOPS) versus fan speeds. Figures 2 and 3 show the HDD performance degradation with increased air mover speed where the air mover is a fan. Lower fan speeds do not generate sufficient noise to couple with the HDD and reduce IOPS.

Other External Disturbances to HDD Performance

Other external disturbances affect HDD performance and should be considered in the design or in the deployment of host systems of HDDs. Low frequency vibration is often represented in RV, which is the traditional physics metric associated with HDD throughput. RV technically refers to rotational vibration, one of six degrees of motion of a rigid body, and, in the context of HDDs, most often around the spindle of the HDD. Low frequency vibration generation and transmission must be controlled but presents challenges, mostly in that the related wavelengths are long relative to control methods. Carefully designed isolation schemes for both HDD carriers and fan mounting can be effective in reducing low frequency vibration content. Another disturbance is noise from fire-suppression systems with sufficient sound pressure levels and frequency content to disturb HDD performance. Sound pressure

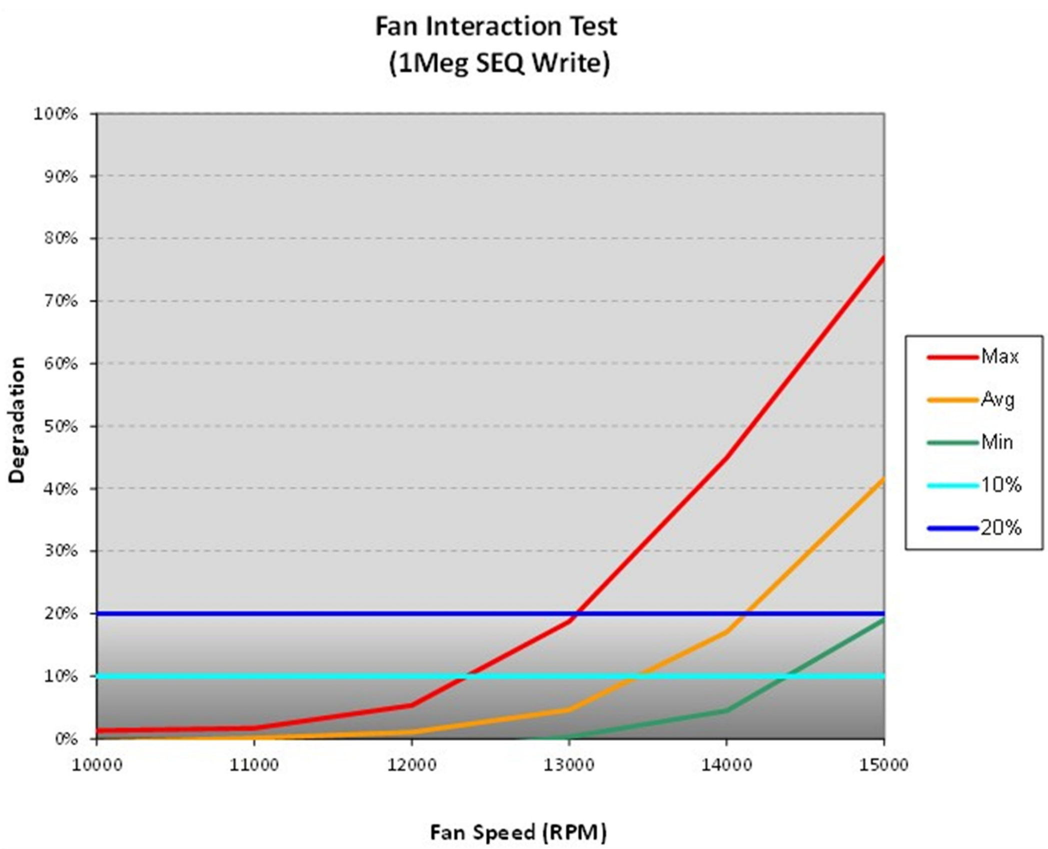

Figure 2 Sample of HDD Performance loss versus cooling fan speed. Degradation is the percent of HDD input/output operations per second compared to a baseline performance of the same HDD. The baseline performance is measured in the absence of external vibration.

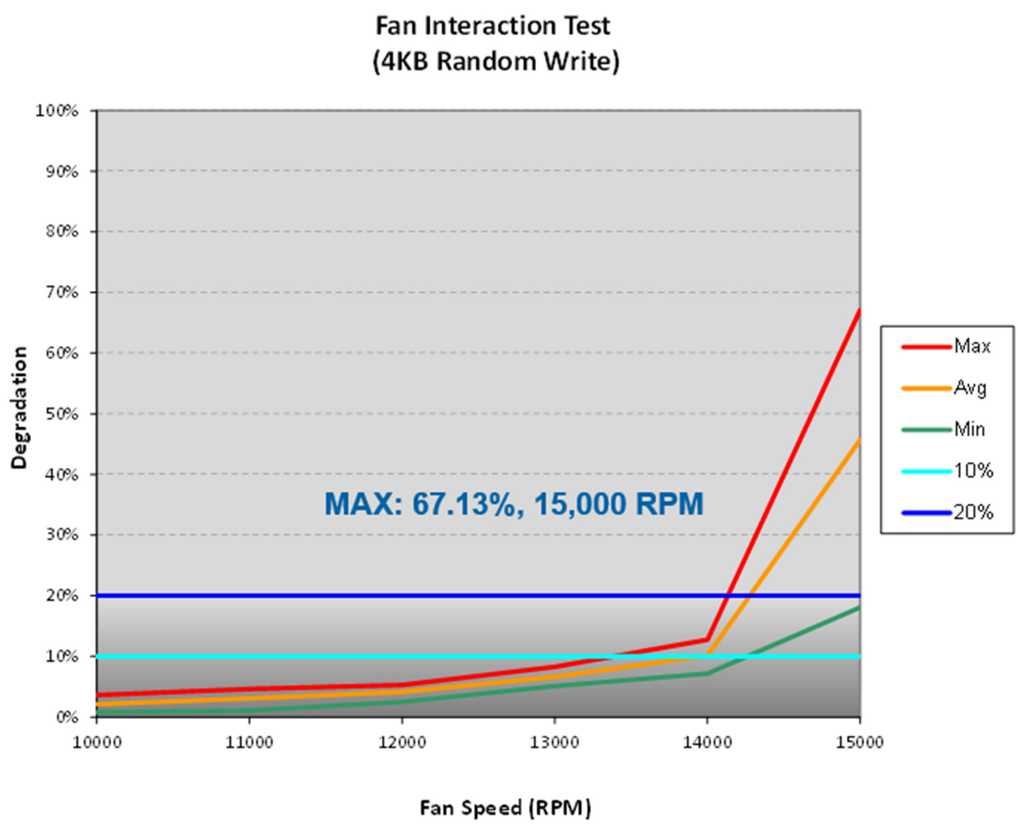

Figure 3 Sample of HDD performance loss versus cooling fan speeds with random writes.

levels and frequency content have been documented to be sufficient to disturb HDD performance. Consideration of proximity of host chassis of HDDs to fire-suppression devices and selection of those with lower-noise nozzles can be beneficial in reducing the risk of this disturbance.

Planning for Disturbances

Both HDD servo-mechanical development and IT system mechanical architecture require multiyear planning and coordination to provide future capability against external excitation. Traditional specifications are helpful for linear and rotational vibration, but newer guidelines or specifications for sound pressure versus frequency need to be considered. The best case scenario to reduce risk is for HDD developers to provide a risk assessment to the system manufacturers and then have the system manufacturers provide guidelines to data center developers and operators.

Trends in Air-Cooled IT Equipment and Data Center Airflow Demand

To meet future computing performance objectives, IT equipment power consumption has been steadily increasing and will likely continue to increase into the future as functions of new workloads and technologies. This growth in power has driven commensurate growth in the airflow requirements of the IT equipment and, subsequently, the required air delivery from the data center. The third edition of the *IT Equipment Power Trends* (ASHRAE 2018 [formerly *Datacom Equipment Power Trends and Cooling Applications*]) Datacom Series book provides power trends for servers, storage, and communication equipment. The evolution of air-cooled IT equipment power trends in 2U 2S servers from 2010 through future projections to 2025 is shown in Figure 4 (ASHRAE 2018).

A review of the data for volume servers over the last five years and projection to the next ten years indicate an overall rise in power of almost all the server workload

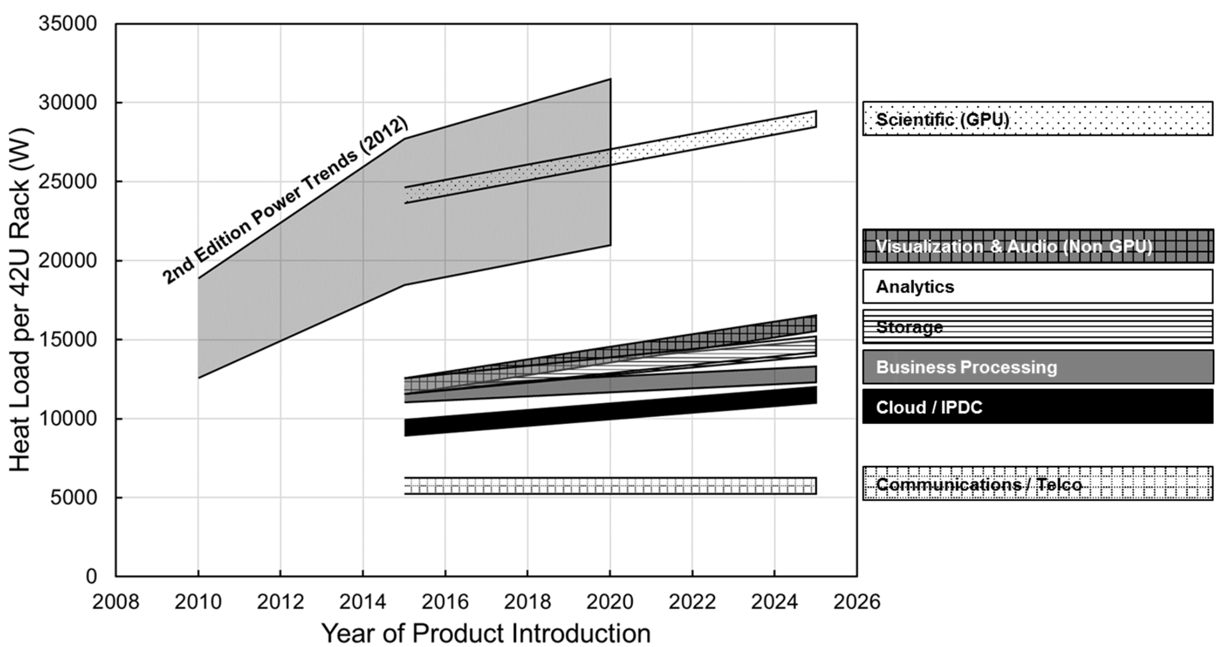

Figure 4 Evolution of ASHRAE power trends from the 2nd Edition to the 3rd Edition of *IT Equipment Power Trends* for 2U 2S servers (ASHRAE 2018).

types. The most striking growth rates occur in the Scientific (4.1%) and Analytics (4.7%) workloads at maximum expected configurations. The higher growth rates can be attributed to the use of higher power CPUs, maximizing the number of components, and the potential for graphical processing units (GPU) being installed. In many of these cases, the power limits already exceed the capabilities of air-cooled data centers (~25 kW per rack). On average, across all workloads and server and storage form factors, the data show that the compound annual growth rate in power is nearly 1.9%.

The impact of the increase in IT equipment airflow to meet these future power trends is critically important to the future reliability of HDDs. Figure 5 (ASHRAE 2018) shows the average expected increase in server airflow requirements (in CFM) for average server configurations by server workload. Most of these projections far exceed legacy or even typical data center airflow delivery capabilities. State-of-the-art, best-of-breed data centers are projected to include these workloads at least at the average power level. However, most data centers today do not provide this capability.

To meet these future airflow requirements, an increase in speed (in RPM) of server AMDs will likely be required, which, based on fan affinity laws, will scale linearly with the increase in volumetric flow rate. Sound pressure level and frequency content will also increase. With the projected rise in heat loads coupled with the flat temperature rise through the server, some changes must occur in the data center to accommodate the IT equipment over the next 10 to 25 years and maintain expected historical levels of equipment reliability.

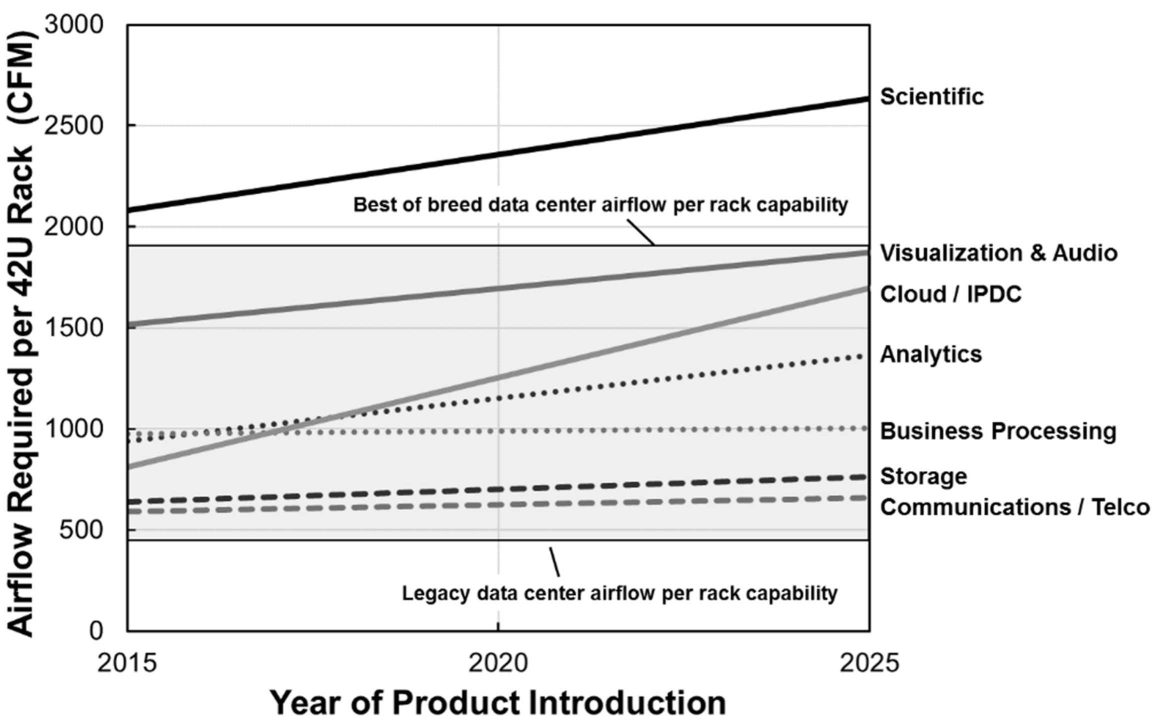

Figure 5 Airflow required per average workload and data center capability (ASHRAE 2018).

Implications to Total Cost of Ownership

Data center designers and operators must study complex total cost of ownership (TCO) calculations to effectively deliver low cost storage and compute applications to customers. These assessments usually include maintaining performance to support service agreements but reducing storage costs, including minimizing capital expenditures and operating expenditures, such as energy consumption. These choices can have a direct impact on hard drives' performance risk unless data center designers, data center operators and IT equipment developers consider these risks as part of the TCO optimization process.

Loss of HDD performance because of external disturbances leads to real economic impact for businesses relying on low latency for applications that affect the customer experience. Whether they are impacts to the customer experience or financial trades, performance loss in the data center has very real economic impacts when high latencies impact customer applications. Data center operators should therefore consider the risk to performance loss as a potential cost of operating a data center.

Both HDD developers and IT equipment developers can provide solutions, but many times these solutions come with some additional cost, and impact the capital expenditure portion of the TCO. HDD development continues to pursue methods of making the drive more robust to disturbances, even as increased tracks per inch (TPI) to attain greater capacities increases sensitivity. But these improvements mean more expensive mechanical and electrical hardware. Solutions such as liquid cooling could remove the need for AMDs, but costs to implement liquid cooling make the TCO effective only with systems and applications requiring high performance that consume significant power for computing tasks and solid state drives (SSD) for storage, while the system level HDD solution needs to focus on providing the most economical solutions for data storage.

In the long term, the optimization between system developers and storage development should follow a plan where HDD robustness is planned and the predicted robustness is communicated to the system designer. The system designer must then evaluate whether the system design allows for the maximum AMD speeds required to cool components and simultaneously yield low risk for HDD performance degradation. Success in limiting performance risk requires that each segment of the chain, from hard drive development to IT equipment and data center development, communicates to fully understand the presented risks to provide a low cost and low latency storage solution.

A side but related implication of the greater demand for airflow is that power consumption to air movers add to the overall increase in server power demand. As power and power density in the server increase, the power law nature of cooling requires a nonlinear increase in airflow and speed of AMDs to produce linear improvements to cooling. To exacerbate this, the air mover power is a cubic function to this nonlinear increase in following speed of AMDs. This is demonstrated in the follow simple example and Figures 6 through 8. Consider a baseline cooling solution which requires 10 CFM to a component to deliver 0.29C°/W cooling capability. If the power of that component increases such that the cooling capability has to be improved from 0.29°C/W to 0.24°C/W, then the airflow needs to be increased to 15 CFM. This 20% improvement to cooling requires a 50% increase in airflow. With the cubic nature of fan power, a 50% increase in airflow would result in a more than 200% increase in AMD power.

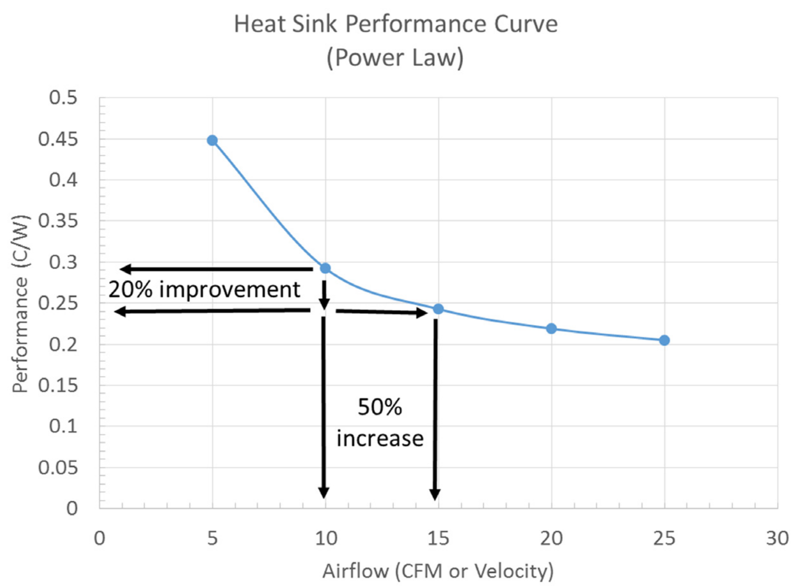

Figure 6 Airflow increase required to improve cooling.

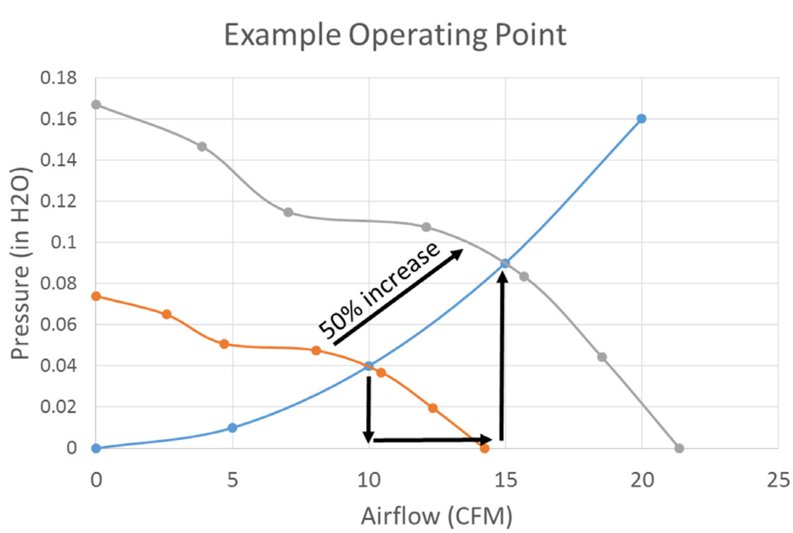

Figure 7 Fan performance increase required to improve cooling.

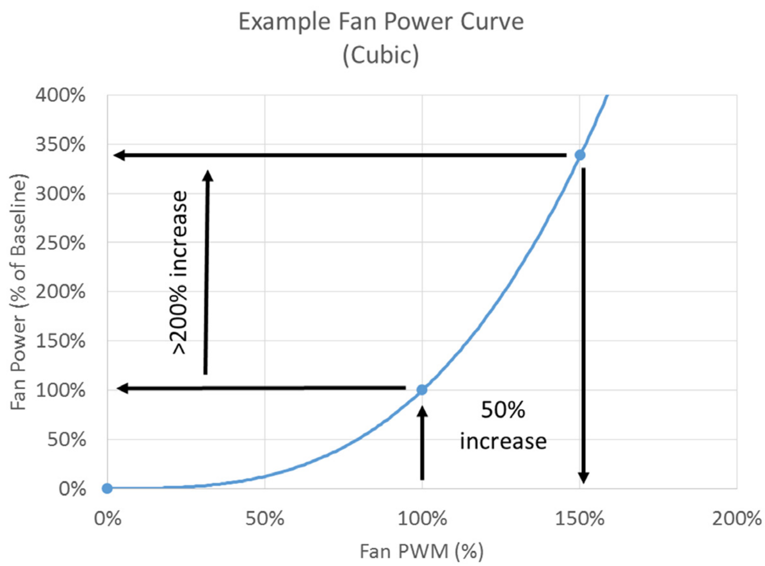

Figure 8 Fan power increase required to improve cooling. *x*-axis PWM refers to pulse width modulation, which controls fan speeds.

Conclusion

HDD performance is sensitive to external disturbances. As capacity increases, the tracks for writing and reading data become smaller, and therefore, the HDDs become even more sensitive to disturbances. Acoustics from AMDs present the highest risk to HDD performance, and the increased speeds required from AMDs to cool, higher powered components in increasingly dense enclosures exacerbate this risk to performance.

Mathematical relationships used to characterize the impacts of the acoustics of AMDs are provided in this paper. Host chassis designers should consider these relationships and plan for means to reduce the content. Moreover, host chassis designers should characterize HDD performance impacts versus the physics inputs, including acoustics, so that they may plan design thresholds that are appropriate for their devices.

In terms of TCO, the impact of the increasing speeds of AMDs on HDD performance may be considered as a companion problem to the impact on power consumption in data rooms or data centers. HDD performance degradation may result in end customer experience issues and long-term reliability issues for the HDD. Those costs should be considered in the TCO discussion to contrast the benefits of cost optimizations such as running with higher ambient temperatures in a data center.

Storage device companies, IT equipment developers, and data center operators and designers must be aware of the risks and collaborate to ensure HDDs have an environment that fosters capacity growth and maintains low latencies to support the needs of the data storage industry. Storage device companies need to continue developing servo-mechanical strategies to maintain performance under disturbance conditions, while IT equipment manufacturers need to design systems with features mitigating acoustical disturbances from air movers through low noise designs and controlling air mover speeds required for cooling.

Glossary

***$/TB*:** Cost of storage in terms of dollars per terabyte.

***air-moving device (AMD)*:** Device that generates airflow for the purpose of cooling components within a system.

***conventional magnetic recording (CMR)*:** magnetic recording technology that uses flux change to induce bits to flip in order to create a magnetic signal based on flux change.

***CPU*:** Abbreviation for central processing unit.

***CRAC*:** Abbreviation for computer room air-conditioning.

***HDD*:** Abbreviation for hard disk drive.

***IT*:** Abbreviation for information technology.

***input/outputs per second (IOPS)*:** Unit of measure for performance of a storage device.

***modal response*:** Shape of vibration to which physical structures tend/resonate for a specific frequency excitation.

***PCI*:** Abbreviation for peripheral component interconnect.

***position error signal (PES)*:** Measurement by the hard disk drive servo system of how far the center of the read-write head is from the center of the data track.

***Rotational vibration (RV)*:** The rigid body rotation of the HDD around disk spindle z-axis.

***TCO*:** Abbreviation for total cost of ownership.

***tracks per inch (TPI)*:** The radial density of data tracks on the disk.