What does Vibration do to Your SSD?

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Abstract

Vibration generated in modern computing environments such as autonomous vehicles, edge computing infrastructure, and data center systems is an increasing concern. In this paper, we systematically measure, quantify and characterize the impact of vibration on the performance of SSD devices. Our experiments and analysis uncover that exposure to both short-term and long-term vibration, even within the vendor-specified limits, can significantly affect SSD I/O performance and reliability.

Keywords

SSD; Vibration; Reliability; Data Centers; Autonomous Vehicles

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1 Introduction

There has been an increasing concern about the effect of noise and vibration on the performance of computing and storage infrastructures from data centers to autonomous vehicles [13, 15, 23]. Recent events have highlighted the significant disruptions caused by noise and vibration to operations of computing centers [11, 24]. Most notable and severely affected examples include the Nasdaq Nordic stock exchange data center in Finland (2018), the Microsoft Azure data center in Europe (2017), and the ING Bank data center in Romania (2016) [23, 25, 26]. As computing and storage devices will increasingly operate in harsh environments such as space explorations, edge computing, and autonomous vehicles [9, 13, 15, 16], the effects of vibration will continue to worsen.

Vibration has been shown to majorly and primarily affect the performance of hard disk drives (HDDs) because HDDs have moving mechanical parts which can be physically perturbed by vibration [5, 6]. However, HDDs are increasingly getting replaced with solid state drives (SSDs) due to their lower I/O access latency and higher I/O bandwidth. SSDs have also been hypothesized to be less prone to vibration related side-effects because of the absence of any mechanical components [6, 21]. This work aims to perform a systematic study to investigate if SSDs are resistant to the adverse effects of vibration. In particular, this is the first work to investigate the following research questions (RQs):

RQ1: What is the impact of vibration on SSD performance (e.g., I/O operation latency and bandwidth)?

RQ2: Does the impact of vibration on SSD performance vary across different SSD vendors and I/O operation types (e.g., read and write)?

RQ3: Is the performance of SSD devices sensitive to the length of vibration exposure?

In this work, we systematically measure, quantify and characterize the impact of vibration on the performance of SSD devices. Our results show that exposure to vibration, even within the vendor-specified limits, can significantly affect the performance of SSD I/O performance. Our experiments discover that the degree of impact varies across vendors and workload types – in some cases, vibration can negatively affect the read/write tail latency by more than 10%, critical for safety in autonomous vehicles [15] and performance in data center computing environments [11]. Interestingly, we also observe that repeated exposure to short-term vibration has lingering after effects on SSD performance even in the absence of vibration. On the other hand, long-term exposure to vibration may result in more than 30% performance degradation. Long-term exposure to vibration can lead to performance slowdowns and abrupt failures, although SSDs continue to function again after a restart.

During this study, we experimented for thousands of SSD-hours with close to one hundred SSDs from different vendors. By the end of it, many SSDs came out permanently bruised due to vibration, and some SSDs succumbed to its adverse effects, despite the vibration being within the vendor-specified limits. We analyzed a large amount of sensor and performance data from these SSDs via various I/O tools. However, we share only selected findings and observations that we could conclude with high statistical significance. Anonymized experimental data is being made publicly available at `https://github.com/GoodwillComputingLab/SSDVibration` for the research community to better understand, model, and mitigate the impact of vibration on SSDs.

2 Background

This section describes the architectural components of a SSD and prior works that study the impact of vibration on storage devices.

2.1 SSD Internal Components

As mentioned earlier, SSDs provide higher I/O bandwidth and lower I/O operation latency than HDDs, and hence, are becoming increasingly prevalent from data centers to autonomous systems. A SSD uses semiconductor chips to persistently store data, as opposed to a HDD, which uses magnetic tapes. The absence of mechanical components distinguishes SSDs from conventional electro-mechanical

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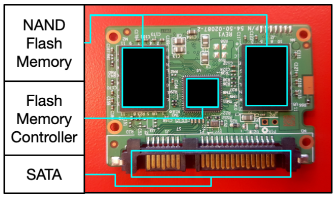

Figure 1: Internal components of an SSD.

HDDs, which contain spinning disks and movable read/write heads. As shown in Fig. 1, the two main components that compose a SSD are the flash chips and the flash memory controller. The flash chips are made of logical NAND gates that store data bits, and the flash memory controller manages all the I/O operations.

NAND Flash Memory is a type of nonvolatile storage technology that does not require power to retain data and uses NAND flash cells to store data. There are different types of NAND flash memories depending on the number of bits stored in each cell and the arrangement of the cells.

The Flash Memory Controller manages the data stored on flash memory and communicates with the compute system. The flash memory controller includes the *Flash Translation Layer (FTL)*, which maps the host side logical block addresses (LBAs) to the physical addresses of the flash memory. This controller is responsible for implementing flash management algorithms such as over-provisioning, wear leveling, and garbage collection. To make the storage device operate properly, the controller maps out bad flash memory cells and allocates spare cells to be substituted for future failed cells from the over-provisioned area. To mitigate write-endurance issues, the controller performs wear-leveling to distribute write I/O operations uniformly to ensure similar rate of aging among data blocks. The controller also periodically performs garbage collection to improve endurance, but it also causes high tail latency.

We note that the flash management algorithms including over-provisioning, wear leveling, and garbage collection have significant impact on SSD performance, but the vendors do not disclose the details of this proprietary information. This limits our ability to identify the root causes and provide explanations for our findings about the impact of vibration on SSD performance.

2.2 Effect of Vibration on Storage Devices

Autonomous vehicles operate in a dynamic environment where vibration, shock, high temperature, humidity and other environmental conditions can affect the computing and storage devices on board [9, 13, 15, 16]. Data centers house a large number of server and storage racks with sophisticated power supply and cooling systems which maintain efficient operations. Thus, data center vibration can be generated via multiple sources including computer servers and power/cooling infrastructure. In a data center, servers with high load, high-velocity airflow, large fans, cooling units, chillers, compressors, and standby power sources can contribute to vibration. Prior related works have attempted to identify the effects of this vibration on different components of the computing and storage systems [6, 24]. These works have observed that the performance of traditional HDDs is significantly impacted by vibration [12]. I/O performance of HDDs can degrade by up to 50% in some cases [7]. Different electro-mechanical faults on storage drives have also been linked to vibration [8, 11, 28].

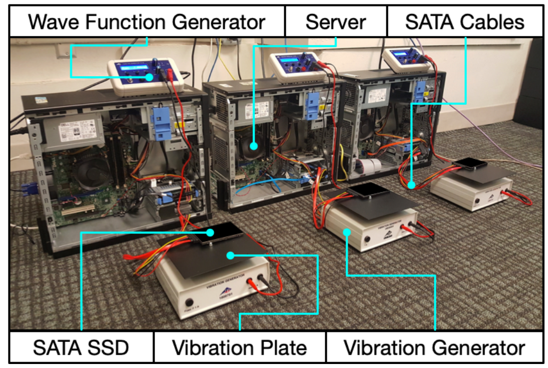

Figure 2: Experimental setup for SSD vibration tests.

As SSDs do not have any moving mechanical parts, they are believed to be more resistant to vibration [6, 21]. However, as discussed earlier, SSDs are composed of sensitive integrated circuit (IC) assemblies for NAND chips and controller – on which effect of vibration is not studied. Therefore, to bridge this knowledge gap, we study the impact of vibration on SSDs.

3 Experimental Methodology

In this section, we describe the experimental methodology to systematically study the impact of vibration on SSDs in our controlled environment. More specifically, we create a controlled experimental setup that enables us to accurately capture and analyze the effect of vibration on SSD performance. Previous works have performed field-studies to observe and analyze the effects of vibration on HDDs in large-scale data centers [6, 11, 24]. However, performing accurate, interference-free and fine-grained experiments to develop systematic understanding of vibration's impact is often not possible in real-world data centers and autonomous vehicles. Therefore, the approach of this study is to draw conclusions via performing controlled experiments on different types of SSDs.

3.1 Experimental Platform Setup

Fig. 2 shows the major components of our experimental platform setup and how these components are connected to each other. The SSD is placed on the vibration plate of the vibration generator. The intensity of the vibration in the vibration generator is controlled by the wave function generator. We place the Operating System (OS) on a separate disk that is insulated from vibration mounted on a rack to ensure that the system kernel is decoupled from the impact of vibration. The SSDs are extended from system connector by SATA extension cables to ensure that none of the system components are impacted by vibration except the SSDs. The SATA cable connecting SSDs is tightly secured to guard it against loose connection problems while performing vibration experiments. We have kept the SSD tight in-place using tapes and metal plates while under vibration. However, we note that tightly packed devices in a data center rack or a moving vehicle are still affected by vibration since not all metals can absorb vibration. Specifically designed racks that absorb vibrations are made of are typically 4x more expensive than traditional racks [2].

We note that the whole setup is inside an isolated room under normal operating conditions, away from other kinds of vibration, heat or external factors that may affect our conclusions. The servers

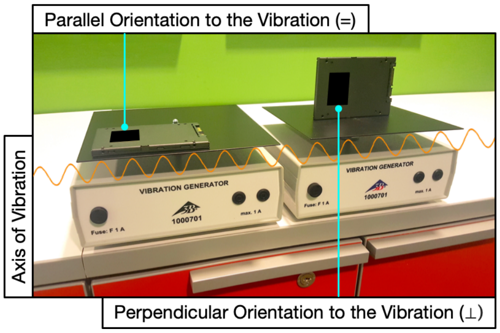

Figure 3: Parallel and perpendicular orientations of the SSD w.r.t. the vibration axis.

are placed on vibration absorbing carpet. We exclusively place only one SSD on single vibration generator to ensure that the magnitude of applied vibration is not dampened because of the weight of SSDs. Throughout our experiments, we preserve SSDs in the same form as what we receive from vendors without removing their IC from the original chassis of SSDs. To generate vibration that replicates data center vibration, we use high accuracy equipment from "3B Scientific". Specifically, we use the FG100 function generator and U56001 vibration generator which can produce sine, square and saw-tooth vibration waves with adjustable amplitude and frequency.

3.2 Vibration Environment

Type: To generate the vibration, we use a classical sine wave (e.g., 60 Hz AC power). We also induced vibrations with different waveforms including square and saw-tooth waveforms and observed that they lead to similar trends and results.

Intensity: We ensure that our vibration intensity does not violate the limit specified in the warranty sheet of the respective SSD vendor. We have chosen 10A-20Hz vibration intensity for consistency across all SSD types, and this intensity is well below the typical threshold specified by SSD vendors [14, 17–20].

Orientation: In a data center, the angle between the axis of vibration and alignment of the components of SSDs can be between 0° to 180° as different servers comprise of different types of rack mounting equipment, and also the sources of vibration originate from different relative angles. Therefore, in this work, to capture real-world settings and tractability for performing experiments, we consider two major angles/types of orientations of SSD with respect to the axis of vibration: parallel and perpendicular.

As shown by the setup of equipment on the left-hand side of Fig. 3, for the parallel orientation of the SSD to the axis of vibration, we place SSD horizontally on the plate that is vibrating in the up-down motion. The short-hand notation used in this paper for representing the parallel/horizontal orientation is the symbol " $=$ ". The right-hand side of the Fig. 3 shows the perpendicular orientation of SSD. The short-hand notation used in this paper for representing the perpendicular orientation is the symbol " $\perp$ ".

3.3 Testbed Setup

Table 1 summarizes the configuration of our testbed. The SSDs are setup as hot plug components to enable and disable their connection to a running computer system without significant interruption to the system's operation. We use open source measurement tools (`dstat` [27], `iostat` [10], `blktrace` [4], `smartctl` [1]) to measure performance metrics. We use SSDs from three different major SSD vendors. For anonymity reasons, we do not disclose the vendor names, but they are major representative SSD vendors who share a large market fraction. We have chosen these vendors to ensure broad coverage of NAND type and variety in the flash management algorithms (although the details are proprietary).

Table 1: Testbed configuration.

Component	Specs
Server	Optiplex9020
Processor	Intel(R) Core(TM) i7-4770 CPU
Processor Speed	3.40GHz
Processor Cores	16 Cores
L3 Cache Size	8192K
Memory Capacity	16GB
Operating System	Ubuntu 16.04 LTS
Kernel	4.4.0-137-generic
SSD Capacity	120 GB
SSD Type	Vendor A, Vendor B, and Vendor C
SATA Version	SATA 3.2, 6.0 Gb/s
Form Factor	2.5 inches
Vibration Wave Type	Sinusoidal
Vibration Intensity	10A, 20Hz

3.4 I/O Workloads

FIO (Flexible I/O Tester) benchmark [3] is used to generate different types of I/O operations via "libaio" I/O engine. We perform direct I/O operations to the SSDs, bypassing the host file system. To emulate the operations of real applications, we configure the I/O depth as 16 and formulate different FIO workloads. We primarily focus on random I/O patterns because random I/O is noted to be more critical for obtaining high performance and challenging to guarantee SLAs for tail latency. Our workload generates random I/O of different sizes from 4KB to 1MB and is composed of both read and write requests. We report I/O tail latency and bandwidth as the primary metrics for SSD performance [9, 11, 15].

3.5 Short-term vs Long-term Vibration Phases

We evaluate the impact of vibration using multiple SSDs from different vendors. For each of our experiments, we use brand-new SSDs which were never exposed to vibration to the best of our knowledge. We precondition a fresh SSD by writing through its whole address space twice to ensure steady-state performance. Then, to explore the impacts of "short-term" vibration on SSDs, we first execute an I/O workload for six hours without vibration for the baseline performance. Then, on the same SSD, we run the same workload for another six hours while vibrating the SSD and compare it with the no-vibration phase performance on the same SSD to avoid manufacturing variability. We chose six hours as the short-term window to attain statistical significance with high number of samples (over 42,000 samples in six hours for each SSD).

We perform this set of experiments with multiple SSDs from the same vendor and observed very small differences in performance across SSDs from the same vendor. If we identified an outlier SSD (inherently slow SSD in a set of large SSDs from the same vendor), we dropped it from our set-up. To study the impact of "long-term" vibration, we execute a workload continuously for 120 hours. We use three separate SSDs to conduct no-vibration, parallel (" $=$ ") vibration, and perpendicular (" $\perp$ ") vibration tests. Again, we carefully conduct our experiments on different SSDs for different vibration types to avoid interference and post-effects of one vibration type on another vibration type. We collect over 840,000

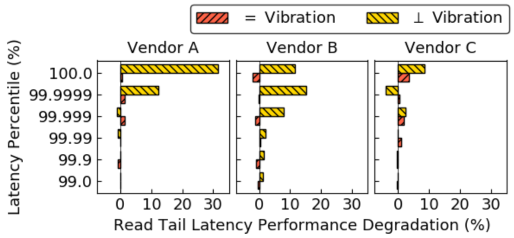

Figure 4: Read tail latencies increase significantly under ⊥ vibration, and slightly under = vibration. Results are normalized to the no-vibration case for respective percentiles.

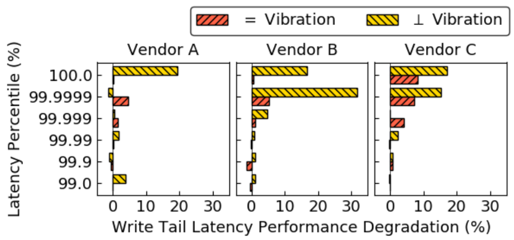

Figure 5: Write tail latencies increase significantly under ⊥ vibration, and slightly under = vibration. Results are normalized to the no-vibration case for respective percentiles.

samples in 120 hours for each SSD to attain statistical significance for the long-term experiments. We also ensure that no SSD surpasses or reaches near its threshold for write-endurance during our experiments. To avoid performance interference for different workloads, we repeat the same experiment process with a new set of SSDs from each vendor and avoid manufacturing variability by discarding inherently slow SSDs under no vibration.

4 Results and Analysis

In this section, we present our results and analysis of the impact of vibration on the performance of SSD devices. We begin by discussing how SSD performance is affected during active vibration. Then, we discuss the post-effects of vibration on SSD performance when the SSD is not under active vibration. Finally, we discuss the long-term impact of vibration on SSD performance.

Effect of vibration on SSD performance during active vibration phase: First, we assess SSD performance by measuring the bandwidth and latency of I/O operations under vibration. We found that the mean performance is not affected by vibration. That is, the mean I/O bandwidth and latency for both read and write operations under vibration are the same as when the SSD is not under vibration. Interestingly, further analysis revealed that while mean I/O latency is not affected, the tail latency is significantly impacted. Fig. 4 and 5 show the degradation in read and write tail latencies under vibration as compared to the baselines, which are the corresponding read and write tail latencies when the SSD is not subjected to any kind of vibration (referred to as "no-vibration"). The degradation in performance is normalized to the corresponding no-vibration percentile value (i.e., our results isolate the effect of increasing tail latency as the percentile number grows and depicts the degradation corresponding to the base case for the chosen percentile). We make several interesting observations.

First, both the read and write tail latencies are affected by vibration. The observed performance degradation can be more than 10% in

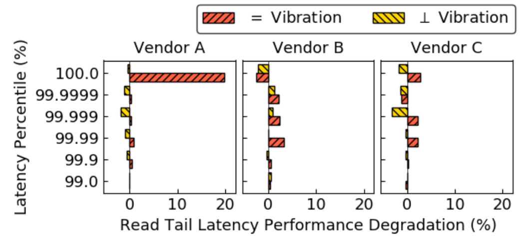

Figure 6: Short-term exposure to = and ⊥ vibration may have post-effect on read tail latencies (even when the SSD is not under vibration).

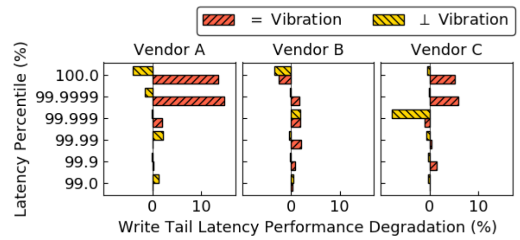

Figure 7: Short-term exposure to = and ⊥ vibration may have post-effect on write tail latencies (even when the SSD is not under vibration).

some cases and upto 30% in worst-case scenario. *Second, all three vendors observe performance degradation in tail latency, although by varying degree and without clear trends.* For example, vendor C shows only small degradation in the read tail latency (less than 5%), but experiences large degradation in the write tail latency (up to 18%). Finally, our results show that *perpendicular vibration has a relatively higher negative impact on the tail latency compared to parallel vibration – this is true almost in all cases, for both read and write operations and different vendor types.* The difference in performance degradation with different orientations can be as significant as 30%.

We examined the SMART attributes to identify hidden patterns and potential root causes. We did not notice any considerable differences in "media-wearout" of NAND flash chip between no-vibration and short-term vibration. Also, we did not find a higher rate of increase in corrected ECC errors under vibration. We theorize that the increase in tail latency under short-term vibration might be due to FTL operations getting affected as the flash memory controller consists of CPUs which are susceptible to vibration effects [22]. However, lack of proprietary knowledge of FTL and flash controller workings limit our ability to pinpoint the exact root-cause.

Post-effect of short-term vibration on SSD performance during no-vibration phase: Next, we investigate if exposure to short-term vibration has any post-effects. That is, how does SSD performance change between two no-vibration periods only apart by short-time exposure to vibration in between.

As the baseline result, we noted that the performance does not change significantly across no-vibration periods when vibration is not applied in between. However, when we apply short-term vibration between the two short-term no-vibration periods, the performance of the second no-vibration period gets affected. Fig. 6, and 7 show the degradation in read and write tail latencies of the second no-vibration period compared to the first no-vibration period when = or ⊥ vibration is applied in between them. Vibration seems to

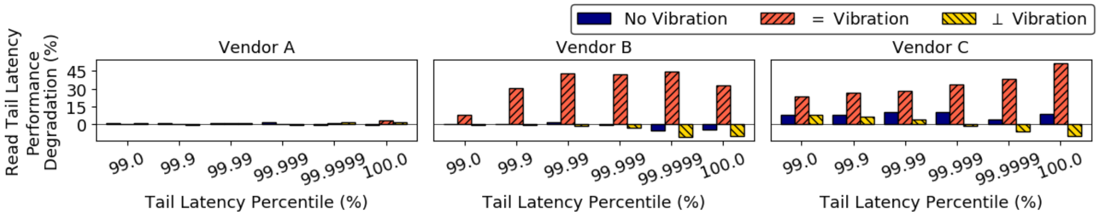

Figure 8: Long-term exposure to vibration significantly degrades the SSD read tail latency under both vibration types. This is especially true for vendors B and C.

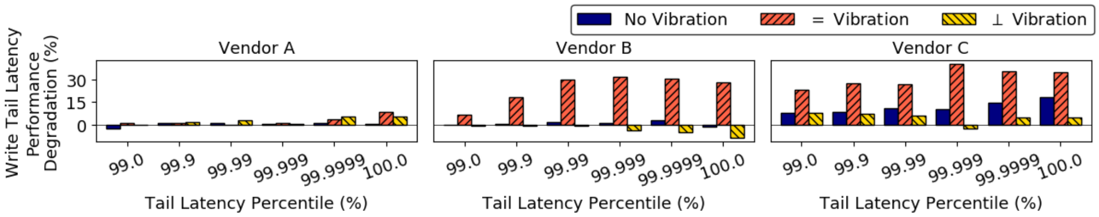

Figure 9: Long-term exposure to vibration significantly degrades the SSD write tail latency under both vibration types. This is especially true for vendors B and C.

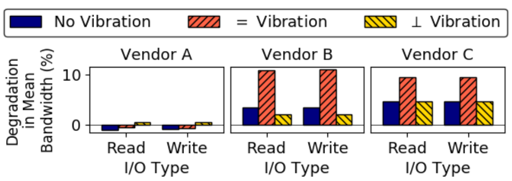

Figure 10: Long-term exposure to vibration can also decrease the mean read and write I/O bandwidth.

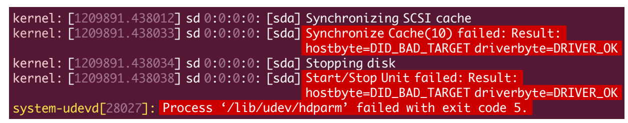

Figure 11: Error reported by syslog upon SSD failure.

maintain some post-effect. However, the magnitude is not as large as the degradation during the vibration period. Interestingly, in some cases, = vibration appears to have relatively higher post-effect than ⊥ vibration, although the effect of = vibration on tail latency during the vibration phase itself is lower than ⊥ vibration. *Lingering post-effects of vibration during no-vibration phases, albeit small but persistent, could be the root cause of fail-slow type performance defects observed in field studies [11].*

Effect of long-term vibration on SSD performance: Motivated by the significant immediate impact of vibration during the short-term, we explore if long-term exposure to vibration affects SSD performance. To capture and compare the effects methodically against no-vibration, we employ multiple SSDs. All SSDs run the same random read-write workload for an equal amount of time; each one-third of the group is kept under no-vibration, = vibration, and ⊥ vibration. Performance after the long-term is normalized with respect to the initial short-term period in each group to avoid manufacturing variability across devices.

Fig. 8, and 9 show the degradation in read and write tail latencies across vibration types and vendors. We make several interesting observation. *First, when the SSD experiences no vibration, the performance deteriorates negligibly over the long term (considered as 120 hours in this study) across all vendor types and I/O operation type. However, the long-term impact of vibration on SSD performance is dramatic, up to 45% in many cases. Second, the degree of performance degradation due to long-term exposure varies significantly across vendors.* Vendor A observes relatively small impact (less than 5%) compared to the other vendors, potentially because of the NAND type (e.g., MLC, TLC). *Third, our results reveal that = vibration has a much higher impact compared to ⊥ vibration. Note that ⊥ vibration results in high-performance degradation in the short-term itself, while = vibration does not. Our result shows that while harmless in short-term, = vibration becomes harmful in long-term, almost as bad as the short-term effect of ⊥ vibration.* The degradation due to ⊥ vibration does not further increase dramatically over the long-term.

Interestingly, we observed that after long-term exposure to vibration, the mean Bandwidth also drops noticeably, up to 10% for = vibration (Fig. 10). While not shown in the results due to space constraints, we observed higher variation in observed bandwidth under = and ⊥ vibration compared to no-vibration after running the SSD for the specified long-term period. We also examined SMART attributes such as - `Media_Wearout_Indicator`, `Available_Reservd_Space`, and `Hardware_ECC_Recovered`, but did not observe any conclusive impact of vibration. This indicates that even when vibration is causing the performance degradation, the corresponding symptoms may not be visible even in long-term via traditional performance and health check tools.

Long-term exposure to vibration can lead to silent failures: We continued our long-term vibration experiments with an intent to let it continue until the SSD wears out by writing more data than what is specified in the warranty sheet. *To our surprise, some SSDs running under vibration started observing silent and transient failures much before they surpassed the write endurance limit and soon after the length of our long-term window.* We note that these failures were not observed in all SSDs under vibration – making it difficult to predict and proactively manage such failures. Also,

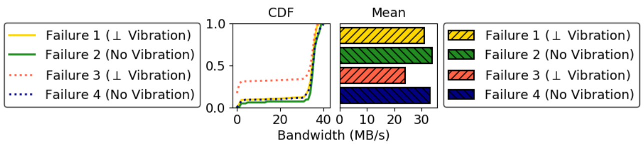

Figure 12: Write bandwidth CDF and mean write bandwidth of vendor A SSD may change in between the stop failures.

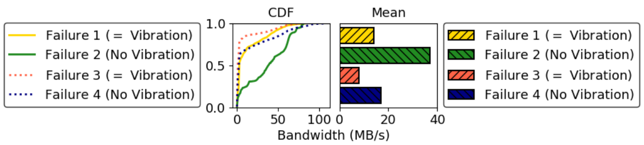

Figure 13: Write bandwidth CDF and mean write bandwidth of vendor C SSD may change in between the stop failures.

our previous long-term discussion did not include any SSD performance data with such failures. On the other hand, any SSD which was under no-vibration did not show any such behavior.

The SSD failures resulted in the running workload being terminated unexpectedly; however, the SSDs worked fine after a restart until the next failure. Fig. 11 shows the the `syslog` snippet for one such occurrence of this type of SSD failure. The error in syslog indicates that the SSD, which is connected as "sda" suddenly goes undetected. Then, upon relaunching the workload, it resumes proper execution. Also, Linux command "lsblk" reports the SSD correctly. Thus, this transient stop fault of SSD is prone to go undetected or be classified as a NDF (no defect found) in the data center setting. We performed more in-depth analysis to understand the performance trend during these transient failures.

Notably, we observed that the performance of SSDs which experience such transient faults drops significantly. Fig. 12, and 13 show the Cumulative Distribution Function (CDF) and mean of bandwidth for two failing SSDs from vendor A and C under different types of vibration, as representative examples. These figures show the performance during the period between multiple transient failures. We make several new observations. First, when we compare the SSD I/O bandwidth without vibration and with vibration, we observe a significant performance drop after the transient failure. Second, between consecutive phases of no-vibration separated by transient failures, the bandwidth decreases by more than 20% in one case. We note that this decrease is larger than the decrease observed in long-term under no-vibration. Upon further inspection, we estimated that the "media wear-out" increases at a higher rate suddenly, despite the fact that SSD should have been far from its write-endurance limit. This is potentially because the damaged NAND cells are replaced by spare NAND cells of the over-provision (OP) region. Essentially, these failures appear to be silent and transient at first but lead to premature death of the SSD eventually as we found in several cases during our study.

Future Implications: Tail latency and performance slowdowns are the most critical factors for both autonomous systems to make real-time decisions and data center providers to guarantee SLAs. Our results show that vibration may have a significant impact on these factors for SSD devices. Thus, storage system researchers and practitioners need to pay closer attention to such impacts for better provisioning and management of SSDs. Our results also indicate that SSD manufacturers need to devise better strategies to contain and mitigate the side-effects of vibration on SSD performance in variable computing environments including autonomous vehicles and data centers.

5 Conclusion

This paper begins by posing a simple question for investigation: "how does vibration impact the performance of your SSD?". We conclude by observing for the first time that vibration can have a severe impact on the tail latency of the SSD and this impact is dependent on the vendor. We discovered that exposure to vibration can, surprisingly, leave post-effects even when the SSD is not under vibration. Additionally, it can damage the SSD performance in the long-term, which has serious implications for data center SLAs and usage of SSDs in autonomous vehicles.

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