Performance Impact of External Vibration on Consumer-grade and Enterprise-class Disk Drives [*]

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Abstract

This paper describes a simple but effective method to generate and observe the effects of external vibration on the read and write bandwidth of a disk drive. Furthermore, it quantifies these effects as a first-order numerical approximation. This paper is not intended to rate disk drives relative to manufacturer, model, size, form factor, ...etc. Rather it is simply intended to answer the simple questions of "Is there a performance impact of external vibration on a disk drive?" and "How significant is that impact?"

After testing several 3.5- and 2.5-inch consumer-grade and enterprise-class disk drives the conclusion is that the consumer-grade disk drives are more sensitive to external vibration. In the presence of an external vibration caused by adjacent disk drive seek operations the bandwidth performance of a consumer-grade disk drive "feeling" these vibrations will decrease about 10%-15% when reading data and about 25%-40% when writing data. The final qualitative result of this study is that disk drive packaging is likely the most significant factor in reducing the vibrational effects.

1. Introduction

Over the past several years there has been a significant decline in the cost of storing data on disk drives. This decline has largely been driven by the high volume market for consumer-grade disk drives for both desktop personal computers and laptops. One result of the availability of relatively inexpensive disk drives is the potential of employing consumer-grade disk drives in enterprise applications. However, the stringent reliability, availability, serviceability, and performance requirements for enterprise-class disk storage subsystems pose interesting engineering challenges to those wishing to build these storage systems using consumer-grade disk drives.

One of these engineering challenges involves the ability of a consumer-grade disk drive to compensate for vibrational "noise" generated by adjacent disk drives in a typical enclosure. It has been "rumored" that this is a significant problem that can cause "performance" degradation and possibly data corruption but there is very little research or empirical data that either confirms or denies any of these rumors. The purpose of this study is a first attempt at an empirical study that qualifies and quantifies the impact of external vibration on the performance and data integrity of a consumer-grade disk drive when operating in an environment similar to that of a typical enterprise disk drive.

Disk drives can be categorized into two relatively distinct groups referred to as Consumer-grade and Enterprise-class disk drives. These two groups are also commonly distinguished by the interface on the disk drive itself being either (1) ATA (AT-Attach) including Serial ATA (SATA) or Parallel ATA (PATA) and IDE (Integrated Device Electronics) or EIDE (Extended-IDE), or (2) SCSI (Small Computer Systems Interface) including Fibre Channel. For the purposes of this discussion however, consumer-grade disks will be referred to as Consumer Storage (CS) and Enterprise-class disk drives will be referred to as Enterprise Storage (ES). The CS and ES distinctions are independent of the disk drive interface thereby removing the terms ATA and SCSI from this discussion[1].

On the surface CS and ES disk drives may appear to be similar but in practice they are very different. These differences are a direct result of the primary requirements that determine the design of each type of disk drive. CS disk drives are designed with cost and capacity as the most important factors whereas ES disk drives are designed for performance and reliability. As a result, it is not a simple matter to replace ES disks with higher capacity, less expensive CS disks and expect the same level of performance and reliability.

One aspect of the performance difference between CS and ES disks has to do with the effects of external

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vibration on a disk drive's read and/or write bandwidth during normal operation. CS disk drives are designed to operate as the only disk drive in an enclosure with little or no sources of external vibration, such as that caused by an adjacent disk drive seeking. ES disk drives on the other hand, are designed to operate in densely packed enclosures with many adjacent disk drives acting as sources of external vibration. The question is: "What is the impact on a single disk drive's performance (bandwidth and I/O operations per second) of the external vibration generated by adjacent disk drives?" Furthermore, "Can this impact be quantified?" In other words, how well do CS and ES disk drives handle external vibration to minimize the performance impact? These are essentially the main questions that are addressed in this study.

2. Our work

In order to answer these questions it was necessary to devise a simple but effective method to observe and quantify these vibrational effects. Therefore, the primary goal of this study was to develop an experimental setup that would (1) demonstrate the observable performance impact of external vibration caused by adjacent disk drives in a worst-case packaging configuration for both CS and ES disk drives and (2) did not require significant funding. It is important to note that this study was not intended to evaluate every disk drive manufacturer and disk drive model, Rather, a small subset of disk drive manufacturers and disk drive models were chosen in order to demonstrate the effectiveness of the test method and to make that test method available to others who may want to pursue a career in disk drive vibration testing.

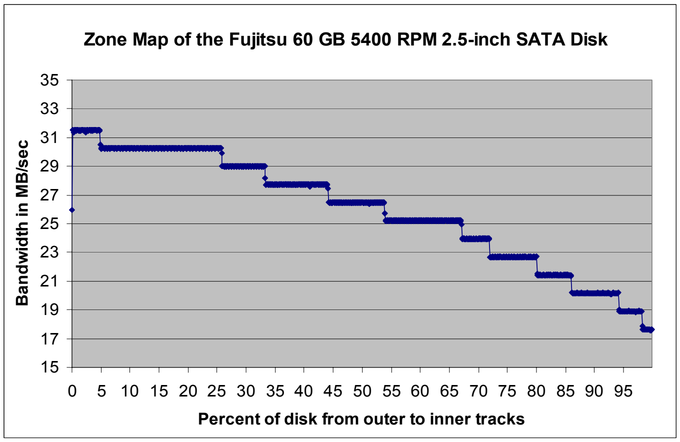
Even though there have been studies and debates over the relative merits of CS and ES disk drive technologies, it is widely believed that CS drives are unsuitable for aggregated storage due to their higher susceptibility to vibration. However, as CS disks continue to increase in capacity and interface performance it is likely CS disks will be used in applications normally reserved for ES disk drives. There is not much public data or research that actually quantifies the effects of vibration on either CS or ES disk drives. For ES drives only one study was found that presents the general effects of vibration. Even in this study, done by Seagate [1], the details are not clear and some pertinent factors covered in this study are not mentioned.

Finally, this study was not intended to directly compare ES disk drive performance with CS disk drive performance. There are many factors that affect a disk drive's performance such as interface protocol, onboard processing power …etc. Instead, this study looks at the relative performance of a single disk drive type from an operational environment with little or no vibration to that of sustained vibration generated by physically coupled adjacent disk drives of the same type as the one being tested. This approach allows us to focus simply on the effects of vibration independent of hardware or protocol differences. It also mimics what would be considered a "worst-case" storage enclosure where the disk drives are packaged so closely that they continually "feel" the vibration of their closest neighbors.

3. Disk Drive Performance

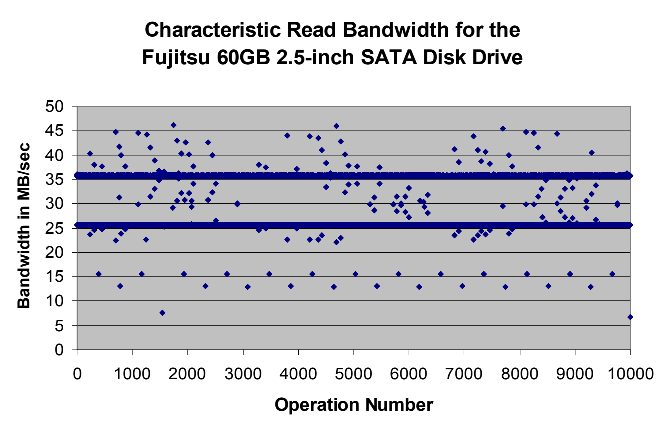
There are many metrics of a disk drive that constitute "performance". The performance metric examined in this study is the data transfer bandwidth for either read or write operations. As it turns out, by measuring the sustained bandwidth of a purely sequential read or write operation, the effects of vibration can be observed and it can be deduced that the degradation is actually related to the seek operations and not the tracking function.

However, the bandwidth of a disk drive is not a simple metric. The bandwidth of any particular I/O operation depends on the location of that operation on the disk drive. A modern disk drive consists of multiple "zones" that are best described as concentric rings on a disk surface. Graph 1 shows how the bandwidth changes as a function of moving from the outer to the inner tracks on the disk drive. There are typically about 16 zones on a disk drive but this varies from vendor to vendor, model to model. For the purposes of this study, measurements were made using the outermost zone unless otherwise noted.

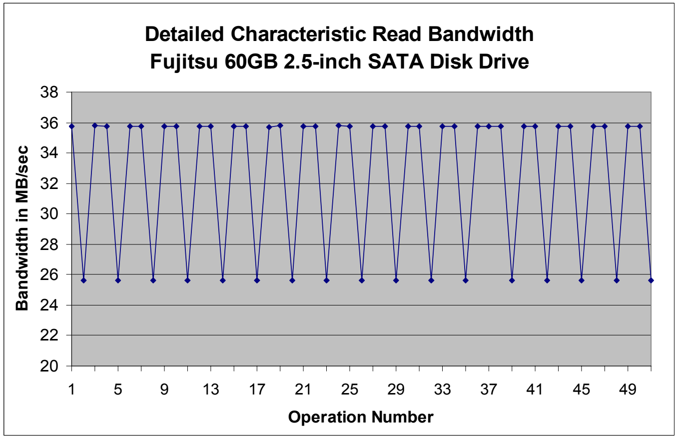


Graph 1. Example of a "zone map" for a Fujitsu 60GB 2.5-inch SATA disk drive. This graph shows twelve distinct "zones" whereby a zone is defined as a contiguous range of tracks that exhibit the same bandwidth. The bandwidth of the outer zone is just over 31 MB/sec and the bandwidth of the inner zone is just over 17 MB/sec. Each point on this graph represents the "average" bandwidth across 60MB of data.

The first part of the experiment was to determine the "characteristic bandwidth" of each disk drive under investigation. Characteristic bandwidth is a plot of the instantaneous bandwidth of individual sequential read or write operations across a given area of the disk. Even though the "average" bandwidth across a specific area of a disk might appear to be a constant value, say 31MB/sec as in the case of the Fujitsu 60 GB 2.5-inch disk drive, the bandwidth of each individual operation is quite different. Therefore, to characterize the bandwidth behavior of a disk, a sequential read of the first gigabyte is performed and the instantaneous bandwidth of each operation is recorded and plotted on a graph. Graphs 2 and 3 show the characteristic bandwidth of the Fujitsu 60GB 2.5-inch disk.



Graph 2. The Characteristic Bandwidth of a Fujitsu 60GB 2.5-inch disk drive. Note the two distinct performance "bands" that appear in this graph. The top band results from read operations that are restricted to a single track and the lower band represents read operations that cross a track boundary.



Graph 3. This graph shows the two performance bands for the first 100 read operations from graph 2. The order in which read operations occur and their relative performance is evident in this graph.

Graph 2 is a scatter graph that plots the bandwidth of each 128KByte read operation against the operation number. In Graph 2 it is important to note the presence of two distinct performance "bands" that occur at about 36 and 26 MB/sec respectively.

Graph 3 is a line graph shows these two bands in detail for the first 50 operations. In this graph it is easy to see a definite pattern of two operations that run at 36 MB/sec followed by one operation that runs at 26 MB/sec. Assuming that 36 MB/sec represents the peak media transfer rate, the time to transfer 128Kbytes at this rate is given by (128*1024)/(36,000,000) which is about 3.6 milliseconds. Furthermore, the time it takes to transfer 128Kbytes at 26 MB/sec is given by (128*1024)/(26,000,000) which is about 5.0 milliseconds. The difference between the two represents the extra time that the lower-performance read operation took to complete. This extra time is simply 5.0-3.6=1.4 milliseconds which corresponds to the amount of time that this particular drive takes to perform a track-to-track seek operation as documented in the specification sheet for the Fujitsu 60GB 2.5-inch disk drive. This confirms the theory that the lower performance band is due to track switching.

Graph 2 and 3 also contain a variety of values that do not fall on either of the two performance bands. This is most likely due to read-ahead caching effects and/or bad sector management operations that occur occasionally while reading a large amount of data from a disk. Since the bad sector mapping is largely inaccessible to user programs and because the methods used are specific to disk drive vendors/models/units it is difficult to identify any specific reasons for each of the points that lay outside the performance bands. At the same time, since there are relatively few of the outliers it is not important to do any further analysis on these points. However, it is interesting to note that in Graph 2 there are a number of evenly spaced points at 13 and 16 MB/sec. Further analysis of these points revealed that they are evenly spaced at 775 requests apart. This is the "signature" of a scratch on the media that extends for at least 1GB into the disk perpendicular to the tracks.

Finally, the same characteristic bandwidth test is performed for write operations. It is important to note that in both read and write characteristic bandwidth tests, the read-ahead and write-behind caches are enabled on the disk drive under test.

4. Experimental Setup and Method

When setting up this experiment it was necessary to determine the effectiveness of the test setup and to define a simple set of tests to run that would provide useful results. This section describes the PC configuration, the test modes, the physically coupling of the disk drives and associated issues, and finally the testing procedure that generated the results described in the following section.

The equipment used in the experimental setup (Figure 2) included:

- 1 Dell Precision 650 PC (one 2.66 Gigahertz Intel Xeon processor) to test the inner drive with its own dedicated disk channel.
- 1.7GHz Celeron eMachines PC used to run the outer drives, each with its own disk channel.
- Platform: Windows 2000 on the Dell, Windows XP on the eMachines
- Benchmark: XDD version 6.2b I/O Performance Characterization Tool

Figure 1 shows the configuration of the test setup. During vibrational test mode the outer drives each perform small read operations at the extreme outer and extreme inner zones of the disk. Each read operation is 4KBytes (4096 bytes). Starting at the outer zone, the operations are interleaved in such a way as to cause the drive to read 4Kbytes, seek to the inner zone, read 4KBytes, seek back to the outer zone, read 4KBytes,… and so on. Each read within a particular zone is randomized in order to avoid any caching effects on the outer disk drives.

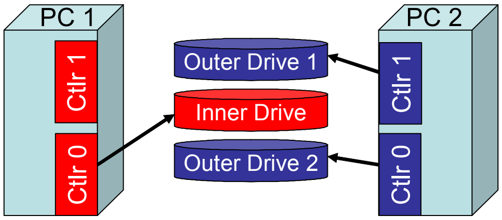


Figure 1. The two outer drives (blue) are used to generate vibration ("noise") that is "felt" by the inner drive. The reason for having two separate systems controlling the drives is to avoid any system contention that can produce misleading results.

The use of two separate PCs was a result of a previous set of experimental data taken from a system configuration with a single PC controlling all three drives. In the single-PC configuration it was noticed that the data transfers from the outer drives caused delays in the data transfers from the inner drive due to process and/or bus contention. This made it "appear" that the inner drive had "slow" transfers. These "slow" data transfers are also the indicator used to identify vibrational noise effects. In a single system configuration it is difficult if not impossible to distinguish a slow transfer caused by contention from that caused by the operation being knocked off track due to vibrational noise. Therefore, it was decided to use two PCs in the test configuration.

4.1. Sources of Vibration

Sources of vibration in a disk drive include self excited vibration such as precession in the spindle motor and platters, platter imbalances, and rotational vibration of the actuator. Many of these vibrations can be transmitted to neighboring disk drives. Of the sources mentioned above, only Rotational Vibration (RV) and the various vibrational modes that it sets up are believed to be of significance in this study.

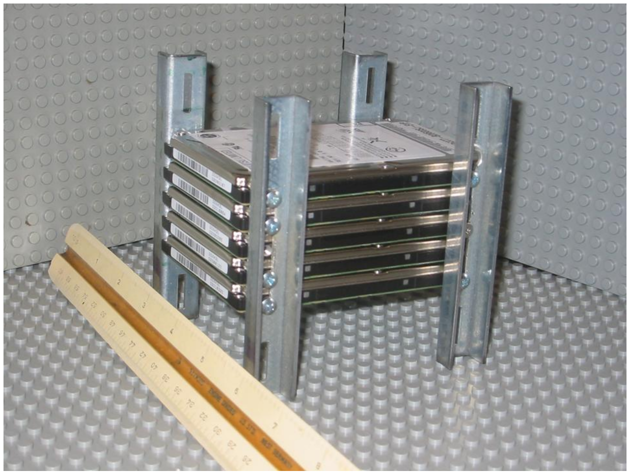


Figure 2. A stack of five 2.5-inch disk drives physically coupled with stiff metal rails.

Figure 3. A stack of five 3.5-inch disk drives physically coupled with stiff metal rails sitting on its side. These rails are made from the same material as the rails on the 2.5-inch disks. The rail material is actually a mounting rail that is attached to a wall and used to hold mounting brackets for shelves.

RV is a twisting/torquing type action generated by a disk drive[2] when the actuator moves from one position to another. Full-stroke seek operations generate more rotational vibration than a single-track seek because of the amount of energy required to move the actuator.

The disk drives themselves were physically coupled using three stiff metal rails on two sides of a group of three 3.5-inch disk drives or two rails on two sides of five 2.5-inch disk drives. The difference in the number of rails used to couple the 3.5-inch and 2.5-inch disk drives is simply related to the number of mounting points available on each type of disk drive. 3.5-inch disk drives have three mount points on each side whereas 2.5-inch disks only have two mount points on each disk. Figure 2 shows the stack of five 2.5-inch disks. Figure 3 shows a stack of three 3.5-inch disks as it sits between the two test PCs and its power supply. Also note that there is a gap between the drives in the configuration shown in Figure 3. The reason for this gap was to test another configuration where the drives were still physically coupled but not touching each other.

Once a group of drives have been physically coupled the outer drives are connected to one of the two PCs (the eMachines PC) and the center drive is connected to the other PC (the Dell 650). Initially, three test modes were examined:

1. Outer drives powered off
2. Outer drives spinning but not seeking
3. Outer drives seeking

In each of the above modes, the center drive is spinning. The first test mode was run and compared to the results of the second test mode in order to determine if there were any observable performance effects simply due to the outer drives spinning. It was quickly determined that there was no difference between mode 1 and mode 2 for all the drives tested. This is primarily a result of the fluid dynamic bearings used on these disk drives which significantly reduces and spindle-induced vibration to the point where it is not an issue for the purposes of this experiment. The remainder of the experimentation focused on modes 2 and 3.

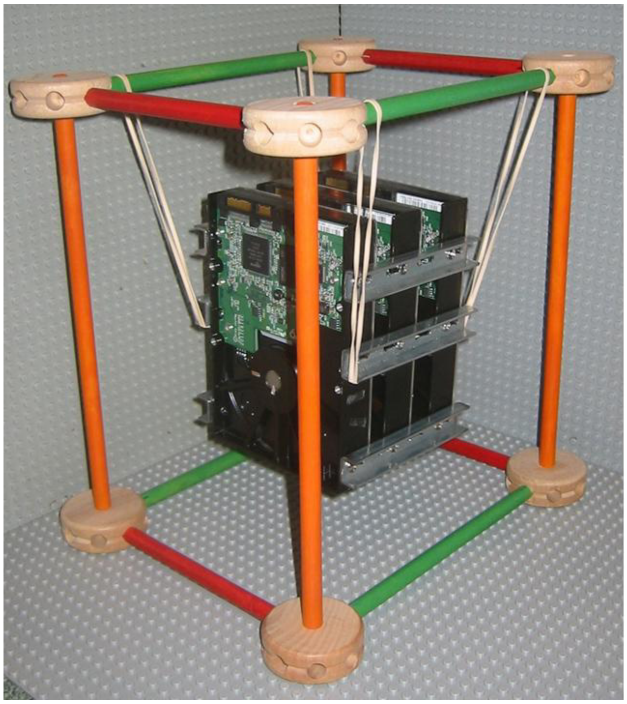


Figure 4. The Suspension Rig used to isolate other sources of vibrational noise.

There were also a variety of coupling modes employed in order to be able to confidently state that the vibrational effects being felt by the test disk were, in fact, due to the two outer drives seeking and not to other external sources of vibrational noise. The other external sources include the cooling fan (not pictured), the test PC’s that shared the same table as the disk stack, and other audio noise in the room (i.e. Jimi Hendrix). To eliminate these as possible contributors, the audio was removed and a suspension rig was constructed and the disk stack was placed in this rig as shown in Figure 4. The results of this test demonstrated that the other external sources of vibration were not significant enough to warrant running all the tests in the suspension rig and that simply sitting the disk stack on the table (as shown in Figure 3) was sufficient for the purposes of this study.

After resolving the above mentioned issues with computer configurations, other external sources of vibrational noise, …etc., the test process was simplified to two steps:

- Run a Characteristic Bandwidth test on a drive stack
- Run a Vibration Test on the same drive stack

The test program used to vibrate the outer disks and to generate the performance data in steps 1 and 2 mentioned above is called xdd[7]. Xdd is an I/O characterization tool that time stamps the beginning and end of each I/O operation issued to a disk drive and writes this time stamp data to a comma-separated-values (.csv) file that was later imported into a spread-sheet program for analysis. These .csv output files also contain the instantaneous bandwidth for each read or write operation which was plotted in graphs for the characteristic bandwidth and vibrational tests.

Each test would read or write data in 128KByte (1024*128=131,072 bytes) requests. This request size is smaller than any track on the test drive and is sufficient to keep the disk drive streaming very close to its peak data rate from/to the media. Each test issues 30,000 sequential requests in three groups of 10,000 requests. In other words, the first pass of 10,000 requests is issued starting at the beginning of the disk and ending somewhere around 1.2GigaBytes into the disk. The second and third passes simply repeat the first pass: starting at the beginning of the disk and ending 1.2GigaBytes into the disk. For most all of the disks tested, 1.2GigaBytes falls within the first (highest bandwidth) zone of the disk drive. The only exception to this is the Seagate 100GB Momentus disk which does not seem to have distinct zones based on the observed zone map. However, the outer area on the Momentus is still the highest bandwidth part of the disk drive.

Each test run produces a time stamp output file that contains, among other things, the instantaneous bandwidth of each of the 30,000 I/O operations performed during the test. The graphs and analysis of these result files are presented in the following section. In general, only the first 10,000 I/O operations are represented in the graphs unless there is a large or anomalous difference between the three sets of 10,000 I/O operations.

5. Experimental Results and Analysis

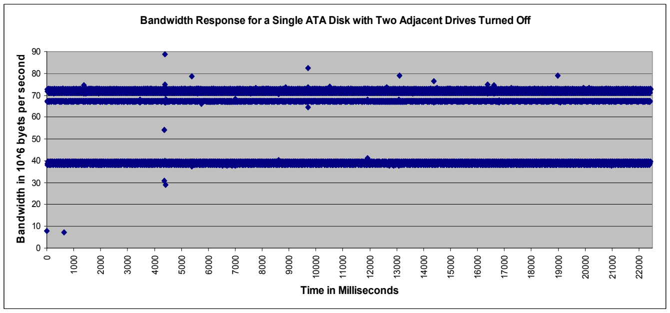
The results presented in this paper represent testing on two 2.5-inch and five 3.5-inch disk drives. Information about these disk drives is provided in Table 1. More detailed information can be found in the individual data sheets for each of these disk drives. The data sheets are available on the websites of the disk drive manufacturers.

Due to limited space in this document it is not possible to present results from all the tests that were run on the disk drives available for this study. However, the intent of this section is to present a number of different test scenarios and related results that capture various dimensions of the vibration problem as a whole.

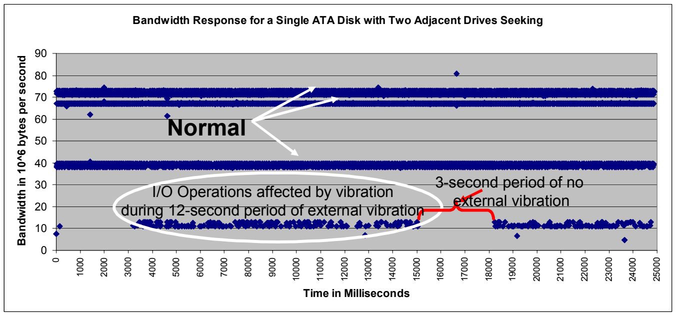
Table 1. A summary of the disk drives used in this study.

Manufacturer Model	Form Factor	Capacity (GB)	Number of drives	Type	Rotational Speed (RPM)
Fujitsu MHT2060AH	2.5-inch	60	5	CS	5400
Seagate Momentus ST9100823A	2.5-inch	100	5	CS	5400
Seagate ST3146707FC	3.5-inch	146	1	ES	10,000
Maxtor DiamondMax9 6Y160P0	3.5-inch	160	3	CS	7200
Maxtor DiamondMax10 6B250S0	3.5-inch	250	3	CS	7200
Western Digital WD2500JD	3.5-inch	250	3	CS	7200
Western Digital WD1200JD	3.5-inch	120	3	CS	7200
Western Digital WD740GD	3.5-inch	74	3	ES	10,000

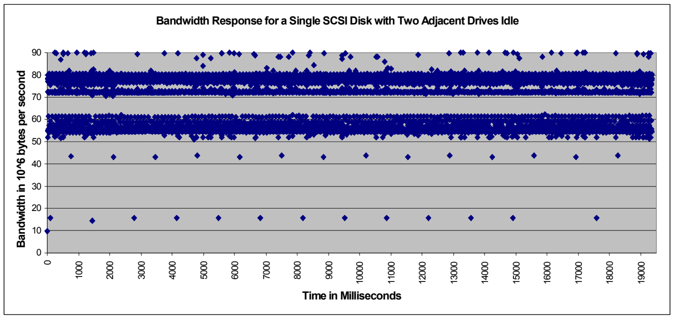
For each set of results the characteristic bandwidth and vibrational test results are shown. Each graph is accompanied with a description of the tests run and some thoughts on the individual results and any anomalies in the graphs. More detailed information including the experimental data is available at *ioperformance.com*.



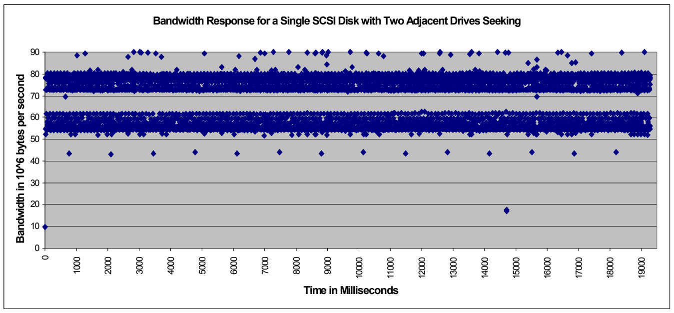
Graph 4. The Characteristic Read bandwidth of the Maxtor Diamond Max 9 160GB CS disk drive.



Graph 5. The effect of external vibration on the read bandwidth of the Maxtor Diamond Max 9 160GB CS disk drive.



Graph 6. Characteristic Read bandwidth of a Seagate 146GB 10,000RPM ES Disk Drive.



Graph 7. Effect of vibration on the read bandwidth of a Seagate 146GB 10,000RPM ES Disk Drive.

5.1. The Maxtor 160GB CS and the Seagate 146GB ES Disk Drives

This section shows the results of the original experiment performed in 2003 to confirm the effects of external vibration on bandwidth performance. Graphs 4 and 5 show the characteristic bandwidth for the Maxtor 160GB disk drive in normal (non-vibrating) mode and during a 12-second period when external vibration is applied. These tests were only performed for read operations.

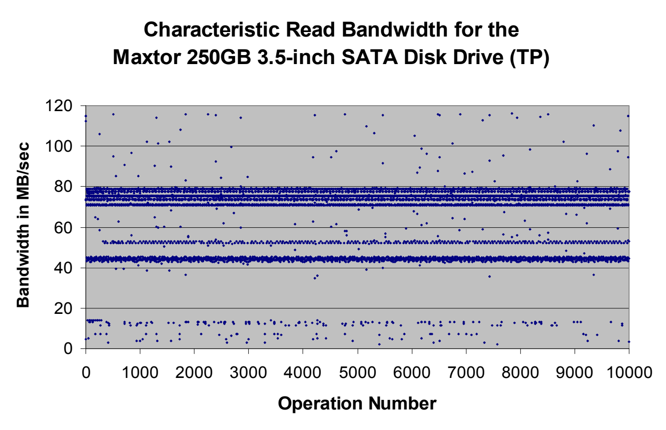
Graphs 6 and 7 show the same test run using a Seagate 146GB 10,000RPM ES disk drive. The result is that the Seagate disk shows no signs of problems with the noise.

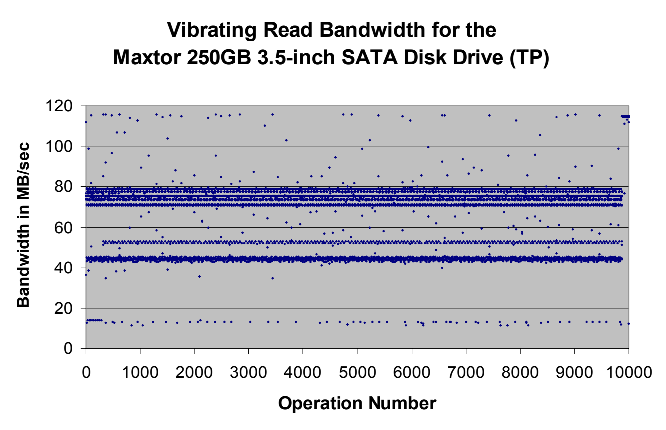
An interesting conclusion from this previous study was that the only read operations that were affected by the external vibration were those operations that crossed track boundaries. This implies that the time the disk drive is most susceptible to vibrational noise is during a seek operation. A detailed analysis of this original set of data confirms this.

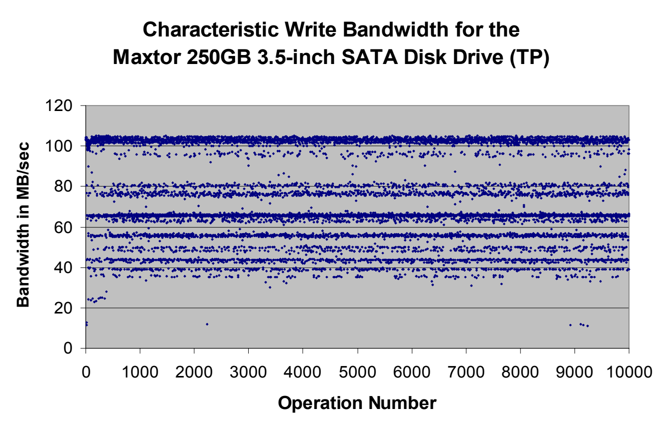
5.2. The Maxtor 250GB DiamondMax10

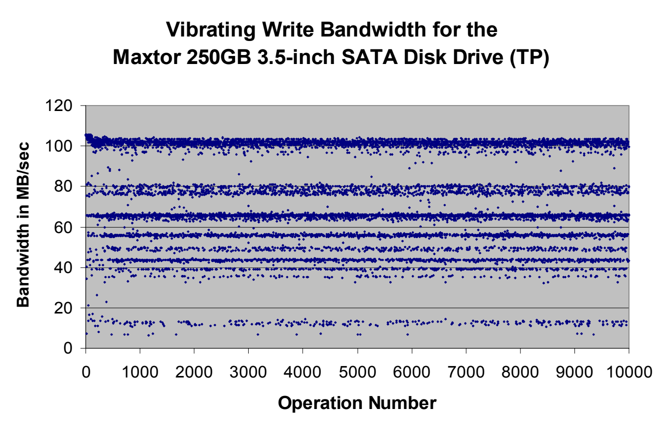
The 160GB disk drives used in the original experiment are about one to two generations behind the most current 250GB Diamond Max 10 disk drives now available from Maxtor. Therefore, it was useful to test the more recent disk drives to see if technology improvements and/or the increase in density have had any effect on the susceptibility of this disk drive to external vibration. The graph set to the right shows the characteristic read and write bandwidth for this disk as well as the bandwidth when in vibrating mode. These graphs indicate that the read operations were not significantly affected by the external vibration. However, the external vibration did have a significant and noticeable affect on the write operations. This is indicated by the presence of many operations the 10MB/sec range which are not present in the non-vibrating mode. The "TP" designation on these graphs indicates that these drives were tightly packed together. A separate test with the same drives involved spacing the drives 1-inch apart as can be seen in the Figure 3. The result of this test showed that the inner drive still experienced vibrational effects on reads and particularly writes.

Since the write operations tend to be more susceptible to external vibration, an important part of this particular test was to perform a data verification test to ensure that external vibration during the write operations did not result in data corruption of any kind. The result of each data verification operation on this and every other disk drive confirms that there was no detectable data corruption caused by the head moving off-track during a write operation and scribbling on an adjacent track. This


Characteristic Read Bandwidth for the Maxtor 250GB 3.5-inch SATA Disk Drive (TP)


Vibrating Read Bandwidth for the Maxtor 250GB 3.5-inch SATA Disk Drive (TP)


Characteristic Write Bandwidth for the Maxtor 250GB 3.5-inch SATA Disk Drive (TP)


Vibrating Write Bandwidth for the Maxtor 250GB 3.5-inch SATA Disk Drive (TP)

is also consistent with the theory from the original experiment that the external vibration only causes problems during a seek operation, probably during the seek/settle time.

5.3. The WD 250GB and 120GB Caviar and the WD 74GB Raptor disks

The experimental setup in for these disks was somewhat different than for the previous disk drives. In this test a total of nine disk drives were physically coupled using longer rails than for the 3-disk tests (shown in Figure 5). The purpose of this test was to determine the effects of additional mass attached to the rails on the drives being tested. The initial order in which the disk drives were placed from top to bottom was:

- Three 250GB Caviar
- Three 120GB Caviar
- Three 74GB Raptors

When testing any group of three disk drives, the other six disk drives were powered off. Thus, when the top three 250GB Caviar disk drives were being tested, the 120GB and 74GB disks were not running.

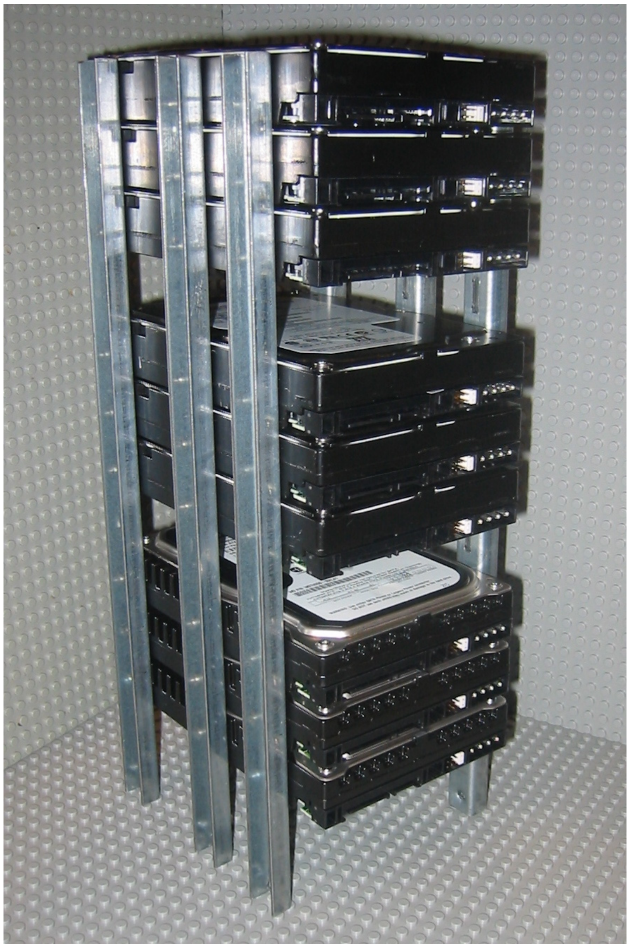


Figure 5. The stack of nine Western Digital disk drives.

An interesting result of this test configuration was that the drives on the outer edges (the 250GB Caviar and 74GB Raptors) showed definite signs of vibrational effects, particularly on write operations, but the 120GB disk drives in the middle showed fewer effects. This lead to reconfiguring the drive stack and swapping the drives in the middle with the drives on top like so:

- Three 120GB Caviar
- Three 250GB Caviar
- Three 74GB Raptors

When the tests were run on this configuration, the outer drives again (120GB and 74GB disk drives) showed signs of vibrational effects whereas the 250GB disks in the center showed significantly less than when it was at the top of the stack. This clearly indicates that vibration transmission through physical coupling can be mitigated by the correct choice of packaging.

5.4. The Fujitsu 60GB and the Seagate 100GB 2.5-inch disks

The 2.5-inch form factor disk drive is commonly used in consumer electronics such as laptop computers. Given the more rugged environment that a laptop poses to disk drive designers, it was interesting to test these disks as well. Five of the Fujitsu disks were coupled using rails as shown in a previous figure. Tests were run in the usual manner but with either 2 or 4 of the outer disk drives vibrating. Even with twice as many sources of vibrational noise the Fujitsu disk drives seemed unaffected.

Similarly, five Seagate 100GB 2.5-inch disks were tested with unusual results. For the most part, the disks did not seem affected by the external vibration of their neighbors but at one point during a write test, the sustainable write bandwidth went to roughly 1/3rd of normal and remained there until the stack of drives was physically moved. The cause of this is still under investigation.

The conclusion regarding the 2.5-inch disks thus far is that they seem to generate less vibrational noise than their 3.5-inch counterparts. This could be explained simply by the fact that the environments they are typically employed are starved for power. Hence the actuators are not driven as hard on full-stroke seek operations and do not make as much “noise”. This too is still under investigation.

6. Future work

The level of detail in the information provided in this study is sufficient for meeting the primary objectives: develop a simple method to generate, observe, and quantify the effects of vibration on the bandwidth of a disk drive. The task now is to incorporate the ability to gather SMART data from the disk drives themselves in order to get a more accurate view of what the disk drive itself is doing when it is trying to compensate for the vibration of adjacent disk drives.

The next step in researching these vibrational effects is to better understand the vibrational modes that a disk drive generates when it is seeking. This includes measuring the frequencies, amplitudes, forces, and energy levels generated by an actuator starting and stopping a seek operation, looking at differences in the acceleration curves of different actuators, and understanding how and where these vibrations are transmitted. This information could also be applied to possibly visualizing these effects in a real enclosure, such as a densely populated rack of disk drives, over all the drives in the enclosure. The effects of two disk drives seeking on a third disk drive are relatively simple compared to those of several hundred drives where the vibrations could easily "destructively" combine to have a significant impact on all the disk drives in the rack.

Finally it would be useful to develop a good understanding about how the vibration problem changes as disk drive form factors decrease and aerial densities increase.

7. Conclusions

As CS disk drives continue to increase in capacity and performance it is becoming more compelling to use these disk drives in applications previously restricted to ES disks. An important issue in disk aggregation is the effect of external vibration from neighboring disks on the delivered performance of the disk drives in the aggregation.

This paper presents a real yet simple procedure to quantitatively demonstrate the impact of external vibration on the different types of commonly used disk drives. Based on the results of these measurements, it was determined that the effects of vibration can be observed and quantified. Furthermore, it demonstrates that CS disk drives are more sensitive to the vibration from physically coupled adjacent disk drives. However, even though the CS drives are more sensitive to vibration, there was no evidence of data corruption when the vibration affected write operations. This leads to the natural conclusion that greater care needs to be taken in enclosure design, particularly for the 3.5-inch form factor disk drives due to their higher-energy seek operations when compared to seek operations on a 2.5-inch form factor disk drive.

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