The Rate of Optical Readout on a Compact Disk

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Information on a compact disk are stored as a series of bumps and flat areas along a helical path. An optical reading device involving laser is used to read the information imprinted on a spinning disk. As the optical reading device moves radially outwards, the angular frequency of the spinning motor decreases to ensure a constant reading rate of information. Though the laser is moving normally to the spinning motion of the disk, the spinning motion of the disk suggests that the reading rate of the laser is the linear velocity of which the helical path is swiped by the laser. The maximum linear velocity of 1.65m/s ± 31.74%, and the minimum linear velocity is 1.43m/s ± 36.82%., with % discrepancies of 15.52% and 16.00% from the range of literature values.

Introduction:

The Compact Disk:

The arrival of compact disks in 1984 signaled the advent of the digital age. New technology has enabled the mass production of compact disks and compact disk players. Compact disks are fast becoming a ubiquitous commodity. Despite the availability and ubiquity of compact disks, few of those who use them understand the workings behind the complex, marvelously high-tech yet low cost equipment.

Employing a wide array of technology, the crisp quality sound delivered by a compact disk player goes through a series of process before reaching the audience's ear. The conversion of sound from digital codes through optical readout is facilitated by the precision of laser readout and the servomechanism that pinpoints the exact location where the laser is and how fast the laser system needs to go.

The main difference between a compact disk and its predecessors such as tapes and vinyl records is the switch from analog to digital technology. In tapes, sounds waves are recorded in their original form via the transmission of a microphone; the blueprint of these waves is physically laid onto the tape. When the tape is played, the waves are read, amplified and sent to a speaker to mimic the original sound. The process involves physical contact between the tape and player in order to produce or record sound. Thus, over time the recording suffers from the wear and tear from physical contact. The wear and tear on the tape add a significant amount of noise as they leave their blueprints as waves on the tape.

On the other hand, the process of digital recording involves the inscription of wave signals in the form of a binary code onto the disk. Thus, the waves are translated into a series of binary code involving 0s and 1s. This is done by forming pits (or bumps looking from the bottom) along spiral tracks on a transparent plastic disk. [Figure I]

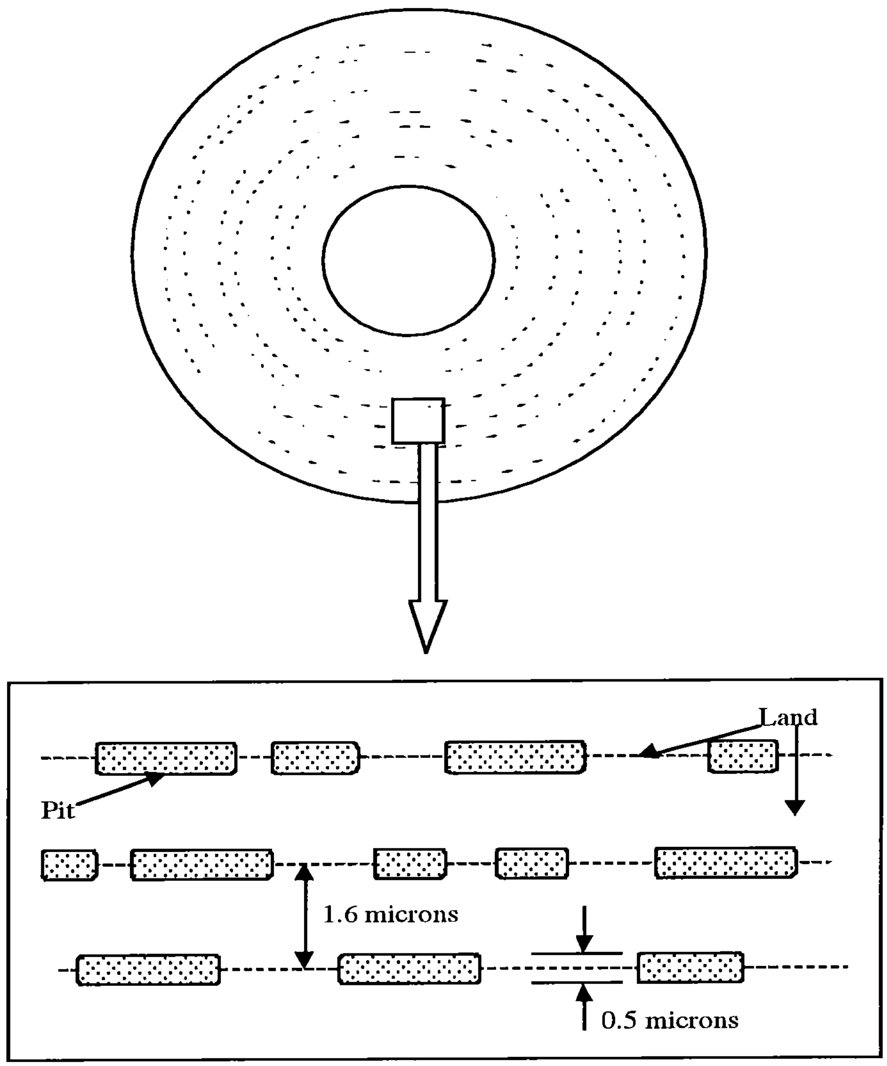


Figure I – Enlarged View of pits along the spiral track

*The pits appear as a series of concentric rings at the bottom of the disk. The magnified section containing pits is shown above.

The pits are actual bumps along the dotted path traced by the laser. The flat area between pits along the path is the land. Thus, the 16-bit resolution of a compact disk means that per second, a combination of 16 spots of pit-land is available. Mathematically, 16-bit resolution means that there are 2^{16} combinations available.

On a given compact disk, the bumps are written onto the disk helically. Due to the microscopic pitch between tracks, the helical path appears almost as a series of concentric rings. The bumps represent the binary code 0, and the flat area represents the binary code 1. In digital technology, the analog wave is sampled at some interval, and then turned into numbers that are stored in the digital device. On a CD, the sampling rate is 44,000 samples per second.

The conventional audio compact disk is a high-density media for storing digitally sampled audio. An audio compact disk typically holds about 74 minutes of music, encoded in digital form with a 16-bit resolution.

Dimensions and characteristics of a compact disk:

Disc:	
Playing time:	74 minutes, 33 seconds maximum
Rotational Speed	1.2 – 1.4 m/sec (constant linear velocity)
Diameter:	120 mm
Thickness:	1.2 mm
Center hole diameter:	15mm
Recording area:	46 mm – 117 mm
Signal area:	50 mm – 116 mm
Minimum pit length:	0.833 μm to 0.972 μm
Maximum pit length:	3.05 μm to 3.56 μm
Pit depth:	~0.11 μm
Pit width	~0.5 μm

Table 1: Specifications for the compact disc system.

*source: Erickson, p. 8.

Reading Mechanism :

In order to read the information encoded on a compact disk, a light beam from a laser diode is utilized. The laser used for the CD player is an AlGaAs laser diode with a wavelength in air of 780 nm. This laser is chosen because its wavelength is one-quarter of the depth of the pit in the medium where it reflects off the surface of the compact disk. The medium has an index of refraction of 1.55. Thus, when laser beams reflect off the surface of the disk containing bumps (pits) and land, the fact that the wavelength of the laser in the medium with an index of refraction of n = 1.55 is a quarter of the depth of the bump (pit) becomes important. This is because the reflection of the laser from the pit and the land travel a path difference of one-half the wavelength of the laser as they are reflected off the pit or the land. The light striking the land travels 1/4 + 1/4 = 1/2 of a wavelength more than the one hitting the pit, so it is 1/2 out of phase with the reflected light from the pit. The difference in their path difference therefore becomes crucial as it becomes the factor in which the two specific waves interfere destructively, as one is in its minimum and the other in its maximum when they meet again, thus effectively canceling each other out. The 16-bit resolution and the varying pit length suggest that the laser reflected back consists of different patterns due to grating and diffraction. The different patterns are picked up by a photodetector and are converted into audio signals. [Figure II]

In actuality, the process is more complicated as the laser goes through a grating that converts the light into a central peak plus side peaks. A twin-grating focusing beam splitter divides the reflected beam into two beams, left and right halves, which are focused onto a pair of photodiodes. The central peak goes through the aforementioned process to achieve and produce the audio output desired. The two side peaks are also reflected and received by the photodiodes, but the main function of the two side peaks is to keep the focus of laser in place. Because there are fewer pits off the track, if the laser is off balance, either too far right or too far left off the track, then the center phototdiode receives too much laser feedback from that direction. Therefore, the two side beams serve as navigators and guide the laser system and ultimately indicate how fast the motor should be spinning the disk. This is the basic idea behind servomechansim. [Pohlman, 93]

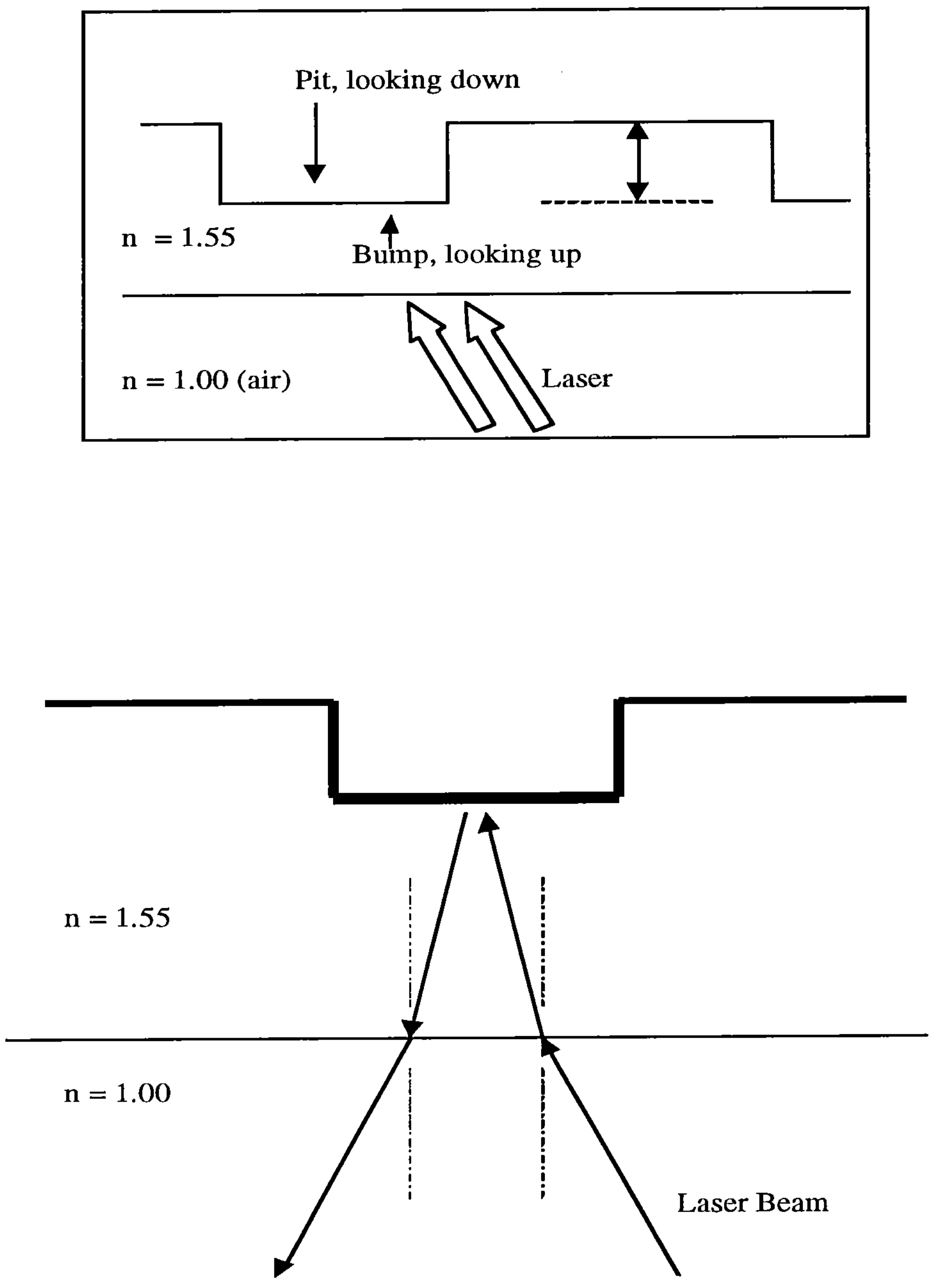


Figure II – Laser mechanism on compact disk

*In actuality, the laser beam experiences diffraction before hitting the surface of the disk. Therefore, diffracted rays hit the surface of the dusk.

why diffraction?

Theory:

In order for the laser system to read the information along the helical path of binary codes, a motor is built in to provide the spindling motion to rotate the disk. Given that information from the compact disk are read at 44, 000 samples per second, the helical path of the binary codes and the spinning motion of the disk imply that the laser system has to constantly move radially outward to read the information. In order for the laser to read the information at a constant rate, so as to produce music at a constant pace, the spindling motor has to adjust the angular velocity according to the position of the laser.

The period in which the disk moves is given by the following equation:

$T = (2\pi r) / v$ -> eqn. 1

r = radial position of the laser system

v = velocity of the spinning disk

The period is also the inverse of the frequency.:

$T = 1 / f$ -> eqn.2

So that $f = 1/T$

Since LabView from Mac calculates the instantaneous frequency using data from the frequency counter, the following formula is used:

$f = v / (2\pi r)$ -> eqn. 3

so that: $v = 2\pi r f$

The literature value of the linear scanning velocity of the laser is given to be 1.2 to 1.4 m/s from table 1, depending on the position of the laser system.

Due to the magnitude of the of the spacing between tracks, which is greater than but comparable in magnitude to the wavelength of the laser used, a compact disk also acts as a diffraction grating when monochromatic light is projected onto the surface of the disk. Using the compact disk as a diffraction grating, the distance between tracks is determined and compared to the literature value.

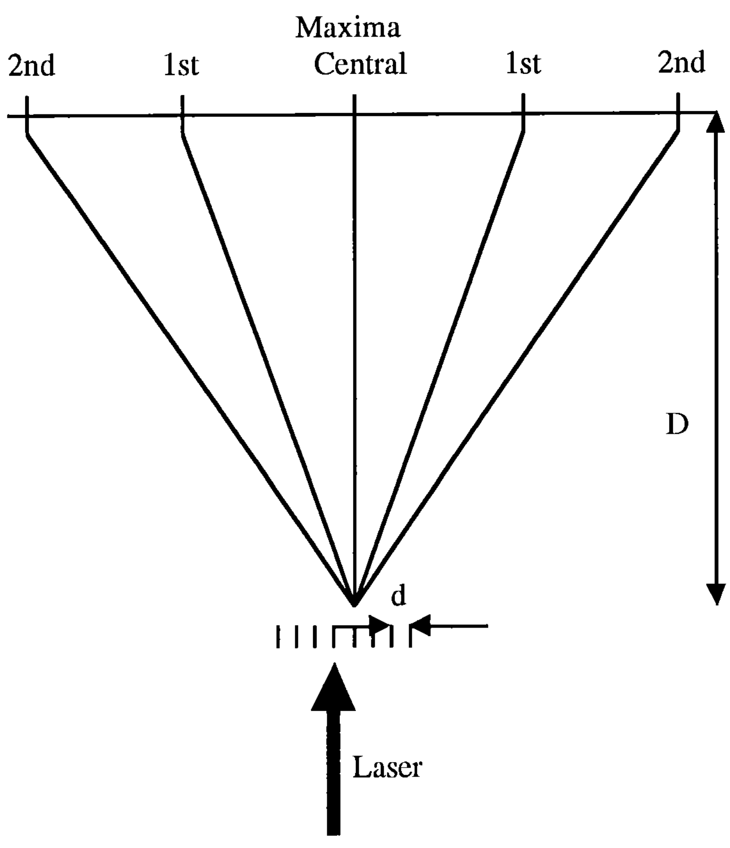


Figure III – Diffraction pattern as a result of diffraction grating on a disk

The diffraction grating spacing of the disk can be found using the following formula:

$d = (m\ \lambda) / \sin\theta$ -> eqn. 4

where d is the diffraction grating, m is the order of maxima, λ is the wavelength of the monochromatic light source. θ is the angle that the first order maxima makes with respect to the center of the diffraction grating. θ is estimated by calculating the ratio of the distance from the first order maximum to the central maximum to the distance between the central maximum to the compact disk (the diffraction grating).

Objective:

The goal of this lab is to determine whether the servomechansim regulates the spindling speed of the motor to ensure a constant reading rate for the laser. The radial position of the laser increases as it moves towards the outer edge of the compact disk when it is played, the spindling motion has to decrease accordingly to achieve a constant linear velocity of the laser system, hence a constant reading rate of 44,000 samples per second.

Equipment:

Helium-Neon laser Uniphase model 155SL-1 – wavelength = 632.8 nm

Convergence Lens

Photodetector

Power Supply – 5 volts , 6A

Hex Scmitt-Trigger Inverter Circuit Board

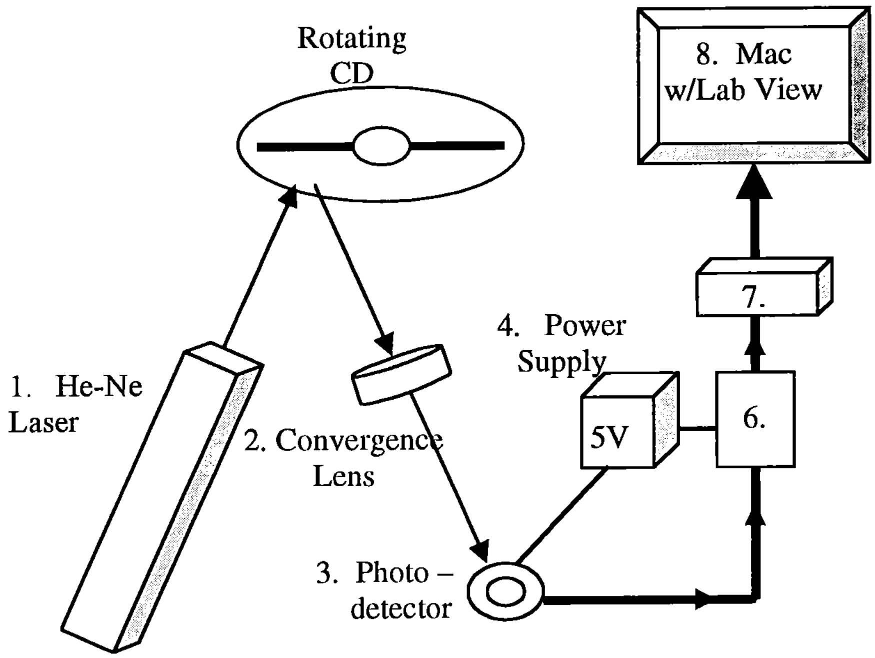
Frequency Counter – Hewlett Packard 5385 A

LabView Program (software)

Compact Disk Player – Sony 85

Compact Disk

Setup:



6. Hex Scmitt-Trigger Inverter Circuit Board
7. Frequency Counter – Hewlett Packard 5385 A

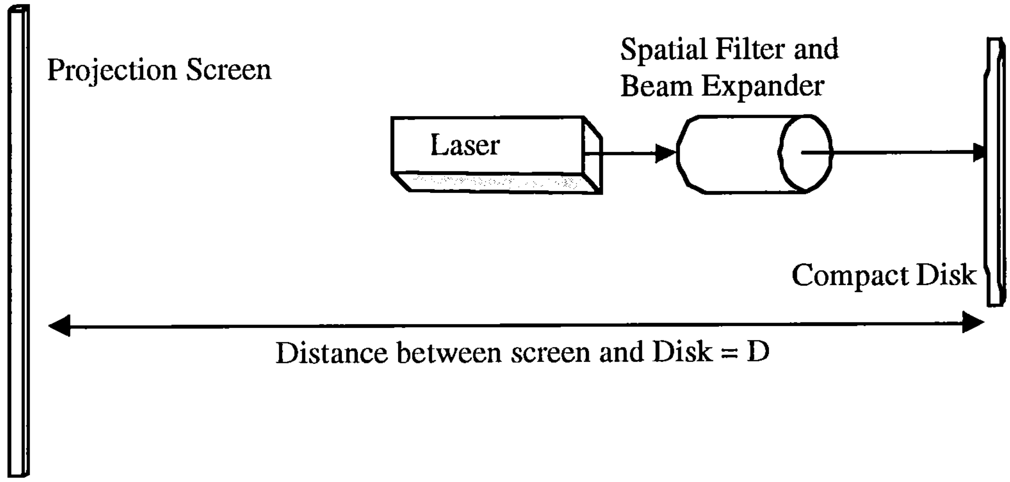
Figure IV – Setup for main experiment

To measure the frequency of the spinning disk, the laser is directed towards the surface of the disk. As the disk rotates, the laser beam is constantly reflected and fed into the photodetector. The photodetector in turn sends signals to the circuit board. In addition, two pieces of black tape line the surface of the disk. The tape serves to kill the reflection of laser, so that when laser hits the tape, no light is reflected, and no signal is sent from the photodetector to the circuit board. The tapes run radially outward and are straddled on two opposite sides so that the laser travels half a disk before hitting the other tape.

The use of two pieces of tape instead of one serves to increase the accuracy in the reading of the frequency counter. Due to the relatively high rotational speed of the disk and the gate time of the frequency counter, accuracy is increased by allowing a greater number of interruptions per rotation (twice per rotation instead of once).

The frequency counter receives constant signals from the circuit board. There are three settings for the gate time, which controls the rate in which the instantaneous frequency is calculated. The three settings are 0.1 seconds, 1.0 seconds, and 10.0 seconds. The frequency counter receives signals from the circuit board and transmits data output to Lab-view in a Mac computer at a rate determined by the gate time. It is crucial to tell Lab View the gate time of the frequency counter so that the output on Lab View would have the same unit of time when frequency is plotted against time. The gate time setting can on Lab View can be adjusted by moving the toggle switch to the desired position.

To measure the spacing between tracks, the compact disk is used as a diffraction grating. The diffraction grating comes from the track spacing of the disk. Using a monochromatic light (laser) to avoid interference, the grating can be calculated by observing the distance of the 1st and 2nd maxima. The grating is equivalent to the spacing between tracks. The following diagram depicts the setup for the determination of diffraction grating, or groove.



grating spacing?

Figure V – Setup for the measurement of diffraction grating on compact disk

The spatial filter and beam expander are used to eliminate second higher order diffractions. Thus the diffracted laser with lesser intensity are eliminated, only the central maximum beam with the greatest intensity is used to determine the diffraction grating of the disk. The resulting focused beam can be adjusted using the spatial filter. The spatial filter has a circular switch that adjusts the size of the output beam.

Procedure:

To test for the rotational speed of the disc, the setup is shown in the "Equipment" section above. Before starting the experiment, the Helium-Neon laser, convergence lens, photodetector and the compact disk player were clamped to ensure that the system was not moved by accident. Clamping the equipment was necessary to ensure that the laser feedback fed directly into the photodetector and registered into the frequency counter.

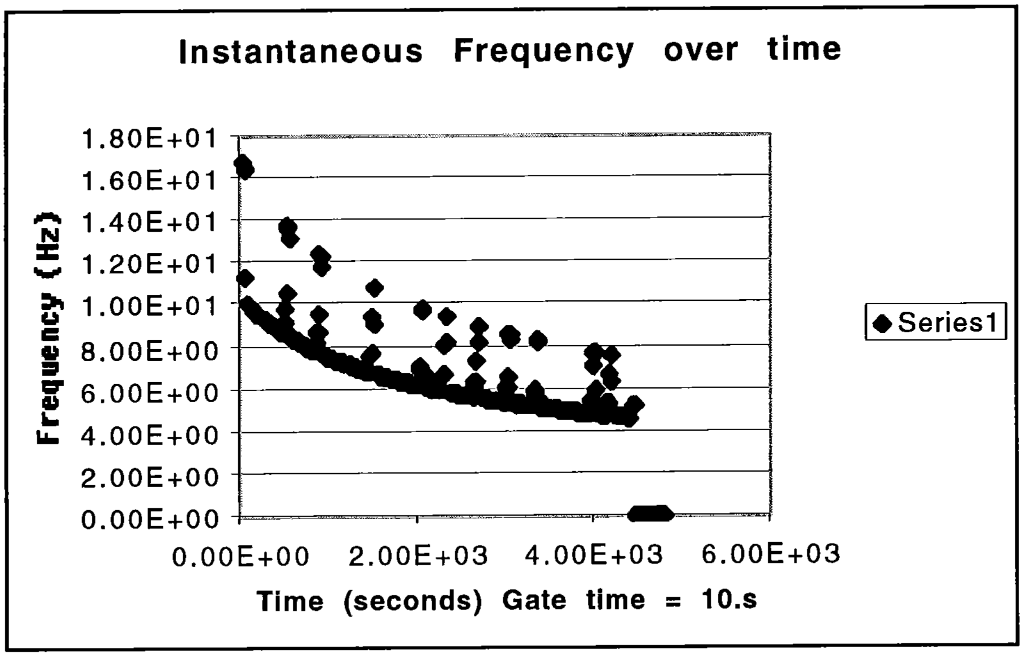
A few test runs were done by running the laser and the compact disk player to check if the frequency counter was receiving signals from the photodetector. The most likely problem encountered when the frequency counter failed to give readings was the lack of focus of the feedback on the photodetector. Thus, before each run, a few test runs were performed to ensure perfect alignment for proper detection of laser feedback.

For each run, LabView was cleared and restarted. While LabView was running the laser was turned on, then the compact disk player was played. These steps were followed to ensure that the data consisted of the disk playing over the entire range of its capacity, implying that the disk was played from its inner most radius of recording (46mm) to its outermost radius of recording (116mm). The compact disk player was played continuously for approximately 75 minutes for the same reason.

The gate time was then changed from 0.1s to 1.0s. And the process above was repeated. For each change in gate time, the frequency counter was readjusted by pressing the "adjust" button and then the desired / corresponding gate time button. In Lab View, the gate time was changed by moving the toggle switch to either one of the three settings: 0.1s, 1.0s, or 10.s. Starting with 0.1 seconds, several results were gathered for each gate time.

Data sets were collected for each gate time. The data collected were automatically graphed by Lab View versus time, so that the general trend of frequency was shown. At least two data sets were collected for each gate time to make sure that data were not spurious. Each data set was then exported to IGOR and graphed.

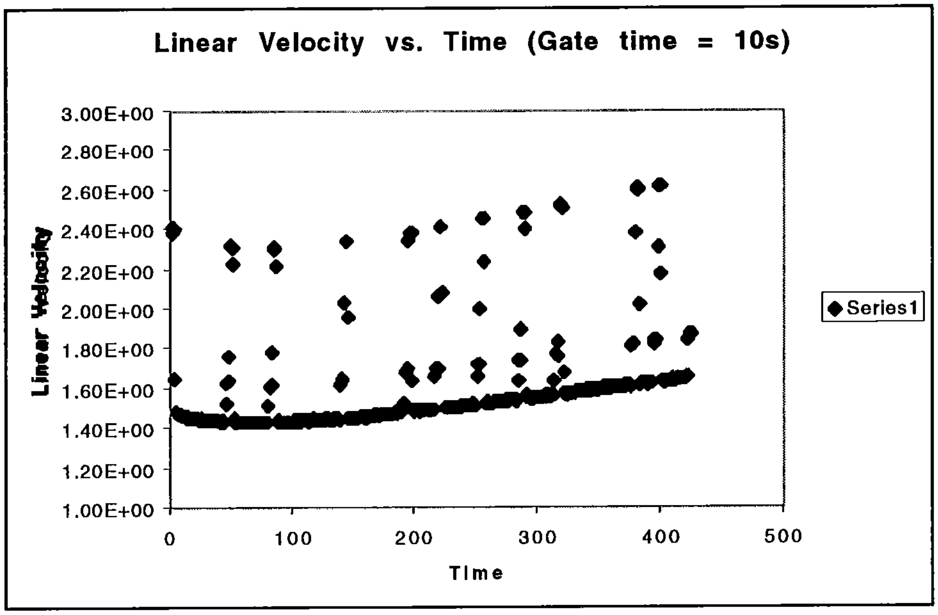
Data Analysis:



Graph I – Instantaneous Frequency yielded by Lab-View

When frequency is plotted against time in IGOR, a definite gradual decrease in frequency becomes apparent. Using equation 3 given in the theory section, the corresponding linear velocity is calculated in the following section. What is also observed in the raw data are the occasional kinks that seem to follow a pattern.

The downward slope of the graph suggests that frequency decreases over time. With the radial position of the laser system increasing over time (as it moves from the inner disk to the outside), the decrease in frequency is therefore offset by an increase radius. Recalling equation # 3: $v = 2\pi\, r\, f$, if the magnitude of decrease in f is matched by the magnitude of increase in radius, velocity would be constant.

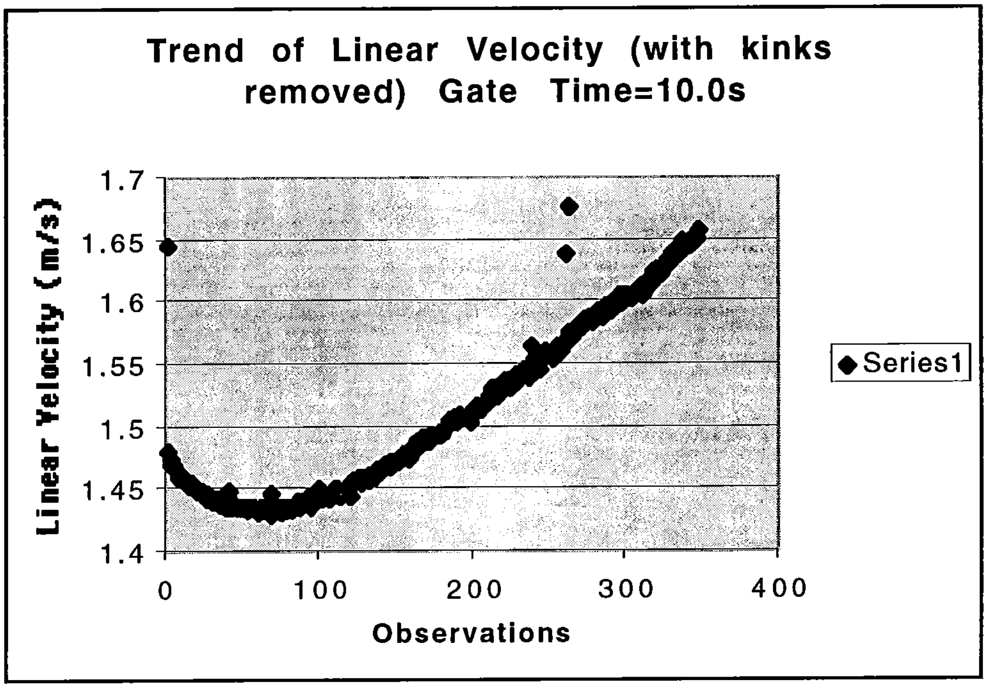


still need units!

Graph II – Trend of linear velocity over time (with jumps in linear velocity)

The instantaneous radial position of the laser depended on the time. Given that the radius had to extend from the inner ring of pits to the outer ring of pits, the rate of the radial movement of the laser was determined. Radial movement is the movement of the laser system from the inner circle of the disk to the outer circle. The radial position was approximated by calculating the distance that laser system has traveled from its beginning position (46mm) times the instantaneous time. Given the instantaneous radial position, the velocity was calculated as well.

In order to determine the reading rate of the laser system, the kinks were removed from the observations and analyzed separately. Thus, the resulting observations excluded the sudden jumps in frequency. The conversion to linear velocity shows an initial decrease then a gradual upward trend in linear velocity. [graph III]



Graph III – Scaled Linear velocity excluding kinks

From the graph, the maximum and minimum linear velocities are determined. The maximum velocity is 1.65725 m/s, and the minimum velocity is 1.42859 m/s. Compared to the literature range of 1.2 m/s ~ 1.4m/s, the results are as follows:

	Velocity (m/s)	Lit. Value (m/s)	Discrepancy (%)
Minimum	1.42856	1.2	16.00
Maximum	1.65725	1.4	15.52

Error and Uncertainty:

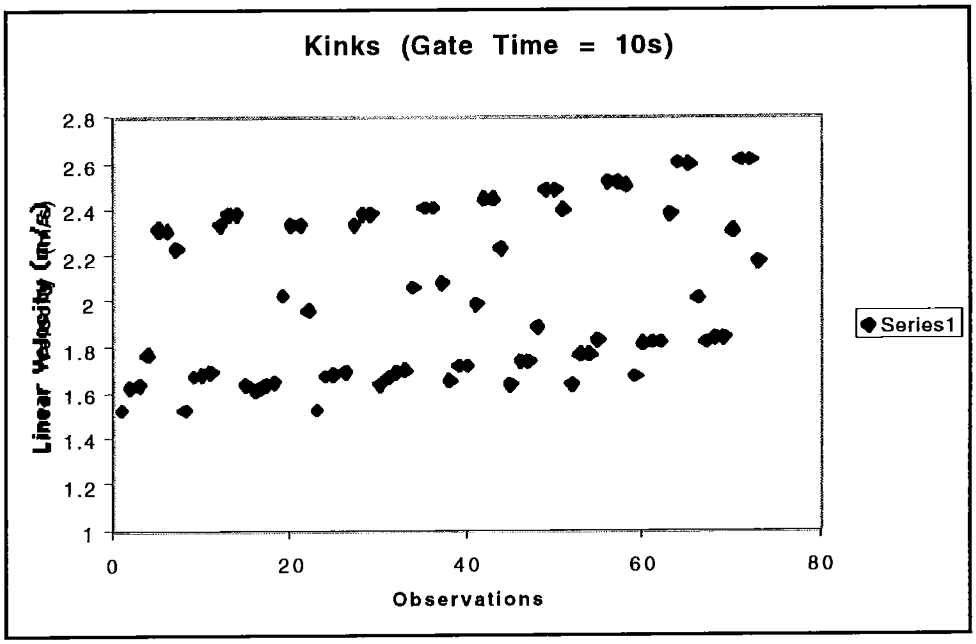
	Frequency	Radius	Velocity
Standard deviation	1.88750888	0.01966309	
Uncertainty	2.80E-01	2.46E-01	5.26E-01

Using the calculated figures above, the absolute uncertainities for the minimum and maximum velocities are caclulated:

Uncertainty for minimum velocity = (5.26E-01 / 1.42856) * 100% = 36.82%

Uincertainty for maximum velocity = (5.26E-01 / 1.65725) * 100% = 31.74%

The corresponding discrepancies of 16.00% and 15.52 % both fall within the range of uncetainty calculated. Thus, the discrepancies are accounted for by the uncertainty.



From the graph, the maximum linear velocity is 2.61m/s. This suggests that at intervals between tracks, the linear velocity, hence the angular frequency of the motor, speeds up. The maximum linear velocity hovers around the range from 2.2m/s to 2.61m/s.

do you mean spacing?

Calculation of diffraction grating:

D (from disk to wall) (m)	3.986
Wavelength of laser (m)	6.3288*10^(-7)

1st Maximum (cm)	1st Maximum (m)	d - diffraction grating (m)
181.3	1.8130	1.44E-06
182.5	1.8250	1.43E-06
179.3	1.7930	1.45E-06
0191.5	1.9150	1.36E-06
184.2	1.8420	1.41E-06
Mean	1.8376	1.42E-06
Standard Deviation	0.02	2.94E-08
% Uncertainty	1.24	2.07

Literature Value of d	1.6*10^-6 (m)
% Error	11.08

Conclusion:

The plotted graphs show a nice consistency of frequency decreasing over time. When the frequency is converted into velocity, the velocity ranges from 1.4 to 1.65 m/s. The values compare favorably to the literature range of values of 1.2 m/s – 1.4 m/s.

When the kinks are removed from the system, what is shown on the graph is the trend of linear velocity consistent with the theory with a maximum linear velocity of 1.65m/s ± 31.74%, and a minimum linear velocity of 1.43m/s ± 36.82%.

The photodetector was very sensitive to light changes. Because the experimental setup was not shielded from external light sources, the photodetector was registering both thelaser reflection and the light in the room. Due to the weak intensity of the light in the room compared to the focused reflected laser beam on the detector most of the time, the data collected had no problem. However, sudden changes in light intensity, such as the turning on or off of external light sources other than the laser used for the experiment , caused some disruption in the data.

One of the interesting outcomes of this experiment was the occurrence of patterned kinks. These kinks translate into jumps in linear velocities outside the literature value. The These kinks occur at between tracks of music, and a careful examination shows that at these intervals, the linear velocity would follow a patterned jump from the average of 1.5m/s to 1.65m/s , to a high velocity of approximately 2.3m/s. The interesting thing is that these jumps occurred several times at 7.2 second intervals. This may be the "reaction" time of the servomechanism and has to be further determined as the track spacing revealed by the diffraction grating of the compact disk was inadequate to explain the interval. The kinks suggest that, between tracks, the lack of bit-land patterns induces the motor to speed through the region as the feedback is interpreted by the servomechanism.

The experimental value of the diffraction grating was found to 1.42267*10(-6) m with an 11.087% error.

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