Examining vinyl noise as proportional to stylus forces

Report for Phys 437B, University of Waterloo

Submitted to Crystal Senko

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Abstract

In this report, the effect of friction on the surface noise of a vinyl record was tested. Previous measurements showed a distinct increase in noise in the right channel of a vinyl record, as well as increased noise near the edge of a test lacquer as opposed to closer to the centre of the record. These differences in noise were hypothesized to be the result of the differences in the force of friction between the turntable stylus as compared to the right and left channel groove walls and tangential speed of the record surface underneath the stylus. The measurements in this report suggest that noise in the right channel while consistently higher than the left channel, is constant with respect to stylus force—while noise in the left channel grows exponentially with stylus force. Using the manufacturer's recommended anti-skate adjustment reduced overall surface noise of the record, and helped to balance the two channels. However, it only balanced them completely at the maximum stylus force of 3 grams and anti-skate set to 3. Noise samples from a small set of records were also taken. Every record had the basic trend of decreasing noise with groove radius, and an average of 1.03 dB greater noise in the right channel. Overall the variation of noise between vinyl records and even noise within the same groove of the vinyl record causes some uncertainty in these measurements and in only a few circumstances could be overcome with analysis techniques.

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Introduction

In this report, the relationship between the surface noise level of a vinyl record and various parameters related to playback were examined. The overall aim of this research is to look into ways of improving the manufacturing of vinyl records in such a way to reduce imperfections, decrease surface noise and improve the listening experience of vinyl records produced in the modern age. In this report, an attempt was made to isolate how different factors of the playback of a vinyl record affected noise levels experienced. The purpose of these experiments is to establish what aspects of the quality of sound reproduction from a vinyl record is due to the consumers equipment and what aspects the manufacturer of the record has control over.

Earlier work in the resulted in the desire to look into the relationship between the forces exerted on a vinyl record during playback and the level of surface noise. As consumer record players can vary in quality quite dramatically, it's important to note what effects different user parameters can have on the playback quality of the record and what the manufacturer of the vinyl record has control over.

Additionally, these measurements help develop some physical intuition into the turntable, stylus and vinyl record system. By understanding the forces at work during playback and how they affect measurable quantities such as surface noise, one hopes to develop some insight into how to reduce the surface noise.

Historical Context

Vinyl records in recent years have made a significant comeback. Their sales hit a 25-year high in 2016[1]. In the age of digital music and streaming, it seems that the segment of music consumers are reaching for an analog copy of music to own and enjoy. This renewed interest in vinyl records presents a unique opportunity to the manufacturers of vinyl records—to revisit this now old process of producing and selling music with modern analysis, materials and techniques.

Experimental and Theoretical Techniques

A vinyl record encodes and then plays back a sound signal in a really unique way. A record begins with a finished piece of music or sound to be cut-- traditionally this was a strip of magnetic tape, however in the modern age it is typically a large, lossless digital audio file.

The digital file is then used by a cutting lathe to physically cut the grooves into a lacquer master disc. This lacquer is typically an aluminum disc coated in cellulose nitrate. This material is soft and malleable to allow the grooves to be cut by the cutting head. The grooves cut to a lacquer can be typically played directly on a turntable-- however since the cellulose nitrate is a soft material, a lacquer is only good for one play through before the grooves begin to wear down. Usually a lacquer is sent to be tested by mastering engineers and before a vinyl record is pushed into full production.

Once a test lacquer is approved, a clean lacquer is cut and then plated typically with a chloride bath and atomized silver in order to harden it for the next stages of production. After the initial silver coating, more metals such as copper and steel, are plated onto the production lacquer. Once enough plating has been applied the lacquer is separated from the plating and a metal negative of the original cutting coated in silver is left over.

Using this negative as a mold, a more durable metal record is made called the “mother”. This record is typically made of copper and plated to be even more durable. It is from this metal mother record that the stampers used to press vinyl records are molded from. A stamper is a metal negative made from this mother. The stampers are then loaded into a record press, and it is the stamper that presses the grooves into the final disk of vinyl.[2]

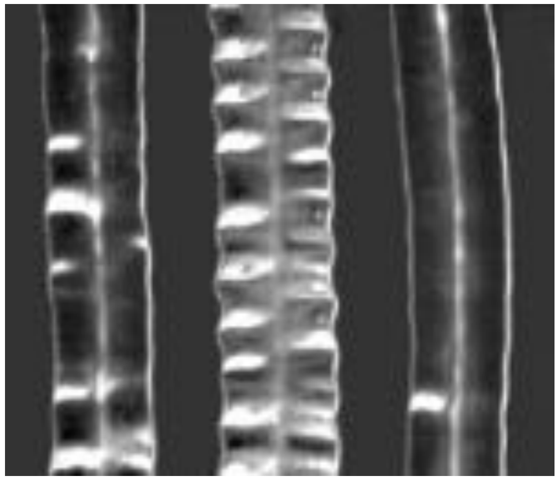


Figure 1: *Typical vinyl grooves on a record.[3]*

Figure 1 shows what grooves that contain music on a typical vinyl record look like. Note the triangular shape of the grooves, this is important as it lets a stereo signal, an audio signal with both a left and a right channel, be encoded onto the record.

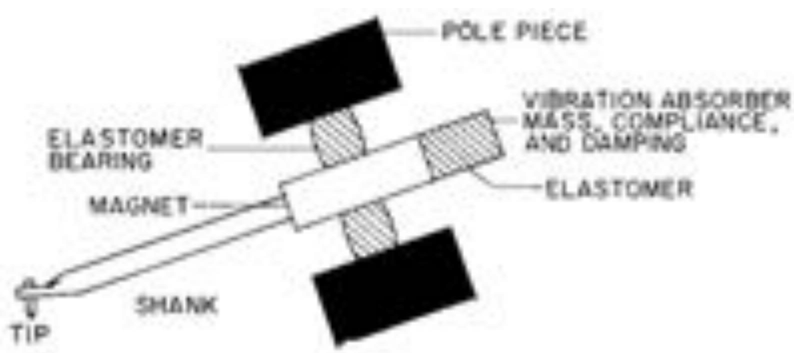


Figure 2: *A diagram of a turntable cartridge, here the stylus is referred to as a shank.[4]*

Figure 2 shows a diagram of a turntable cartridge. The tip of the stylus fits into the grooves of the record. As a record plays the grooves cut into the record move the tip of the stylus both laterally and vertically. This movement is picked up by magnets in the phono cartridge, and translated into a voltage signal to be amplified and reproduced by speakers.

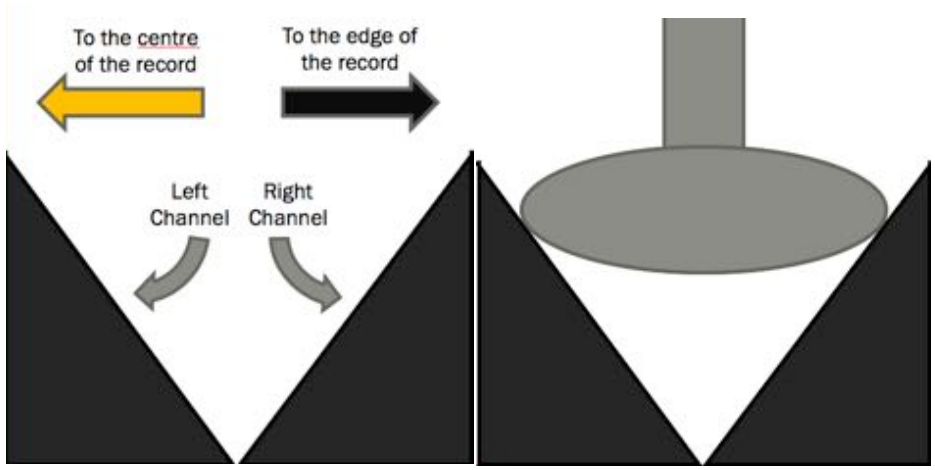


Figure 3: *A diagram of a vinyl record groove, including how the stylus tip fits into the groove.*

This method of encoding a stereo signal onto two walls means that the vertical movement of the stylus is a signal common to both channels and lateral movement of the stylus is signal that is different in the two channels. This will become important, as this report looks at the forces exerted upon the groove walls and their effect on surface noise.

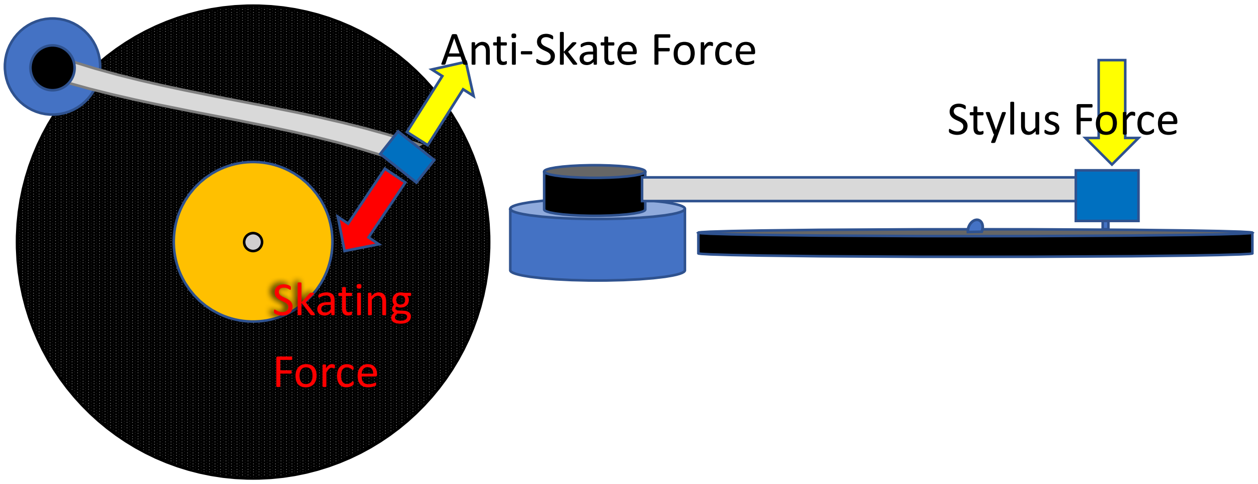


Figure 4: *A diagram of the forces being exerted as a record is played. The yellow arrows represent forces that the turntable provides and the user can adjust.*

During playback, there are three main forces that were the focus of this report. The stylus force downwards, the skating force inwards and the anti-skating force outwards which counteracts the skating force. Both the stylus force and the anti-skate force are provided by the turntable, and most consumer turntables allow the listener to adjust these forces. The skating force however is a result of the force of friction between the stylus tip and record surface. This friction tends to pull the arm of the turntable towards the centre of the record. This force is believed to cause uneven wear on a record and inferior tracking of the vinyl grooves, which is why it is usually compensated for by the turntables anti-skate adjustment.[5]

This report, is looking to these forces as they relate to the surface noise. In order to make these measurements of the noise in “silent” grooves of various vinyl records or recorded and measured under various turntable conditions.

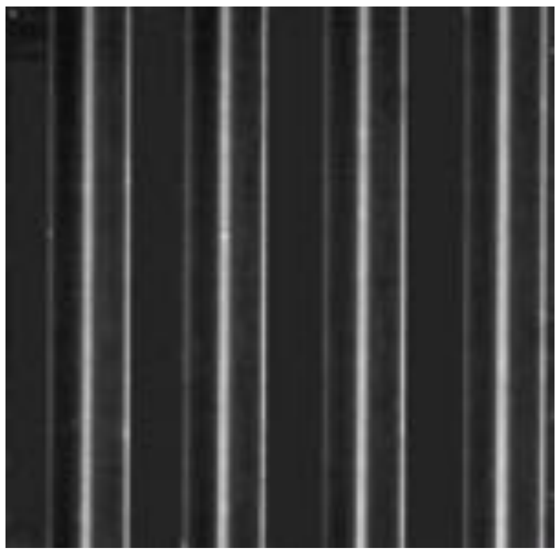


Figure 5: *Quiet grooves cut into a vinyl record.*

Silent, or more accurately quiet grooves, refer to grooves cut to a vinyl record that contain no audio signal, they are typically found in between tracks on a record. These grooves should ideally, result in no movement of the stylus and therefore no audio signal. However, with a real vinyl record that is not the case. In fact, these silent grooves give the best opportunity to sample the noise of a vinyl record, noise that would otherwise be drowned out by an audio signal.

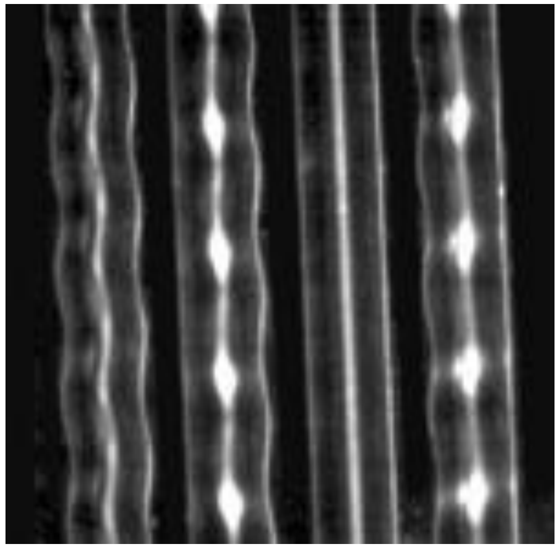


Figure 6: *Sine waves cut onto a vinyl record. From left to right: a sine wave cut to both channels, a sine wave in the right channel, a silent groove and a sine wave cut to the left channel.*

For the measurements in this report silent grooves, like the ones pictured in *Figure 5*, were recorded by our experimental setup.

Our experimental recording setup utilized the following equipment:

- A Technics SL1200GR turntable equipped with an Ortofon Blue phono cartridge
- A Sharp Optonica SM-1400 Phono preamp
- A Focusrite Scarlett 2i2 to record the signal digitally for analysis

Since the primary measurements in this report are volume levels, before each measurement a normalization signal was first recorded. This signal was a 1 kHz sine wave at 2.4V RMS produced by an oscillator and verified using a voltmeter. This signal was chosen as a 1 kHz tone is a typical reference tone for audio systems[6], and 2.4V was a typical voltage measured coming from a vinyl record through our system.

In order to ensure signals could be accurately compared with one another, each signal was normalized such that the normalization signal was record at -3 dB in the system.

A sample of noise from the system was taken by simply recording the inputs of the system into the Focusrite with the needle of the turntable up, and no record playing. This recording was then compared with a typical recording of vinyl surface noise, showing that the noise of the preamp, turntable and audio Focusrite are well below the noise being measured from the record.

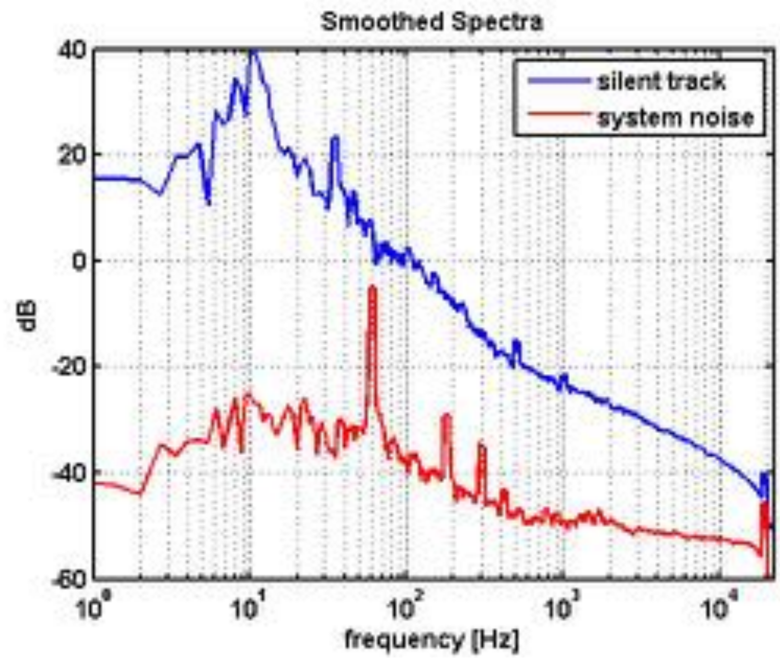


Figure 7: *A comparison of the system noise of our recording setup versus a typical sample of vinyl noise.*

An interesting thing to note, the system has a distinct hum at 60 Hz. This is AC hum and is believed to be a grounding issue inside the Optonica preamp. However, it is well below the signals being measured and as such its effect on measurements should be negligible.

The results from the previous 437A project are best summarized in the plot below. In 437A a test lacquer was cut containing various signals produced in Octave MATLAB. The surface noise of the test lacquer for the two channels was measured, and then plotted as a function of playback time.

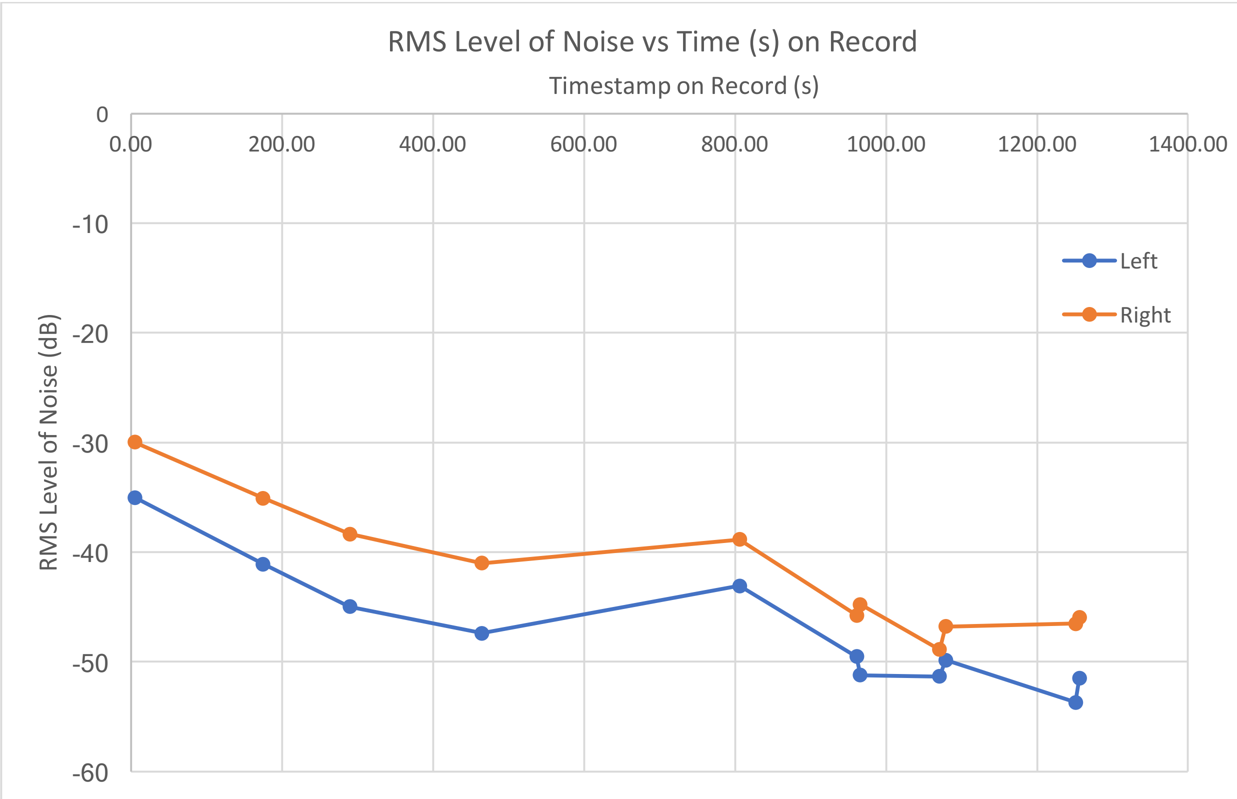


Figure 8: *RMS noise level as a function of time of the test lacquer used in the 437A report.*

Here the noise level was sampled at various points along the record and plotted. As shown the noise was always higher in the right channel than in the left channel and noise seemed to decrease as the tonearm moved closer to the centre of the record.

The hypothesis put forward in my 437A report is that the noise was proportional to the force of friction between the stylus tip and the record. This force of friction would be proportional to the force exerted onto the record by the turntable including the skating, anti-skating and stylus force—as well as the speed of the record surface moving underneath the stylus. A record is spun with a constant angular velocity, so the speed of the record surface is directly proportional to the radius that the stylus is on the record.

While analyzing the recordings made for this report we developed a very interesting and useful analysis technique that greatly improved the precision of our measurements, and provided some insight into the nature of vinyl surface noise.

Initial attempts at plotting surface noise at different stylus forces, while promising, showed way too much scatter to reveal any meaningful trends. In *Figure 9* multiple recordings at different stylus forces were done and plotted.

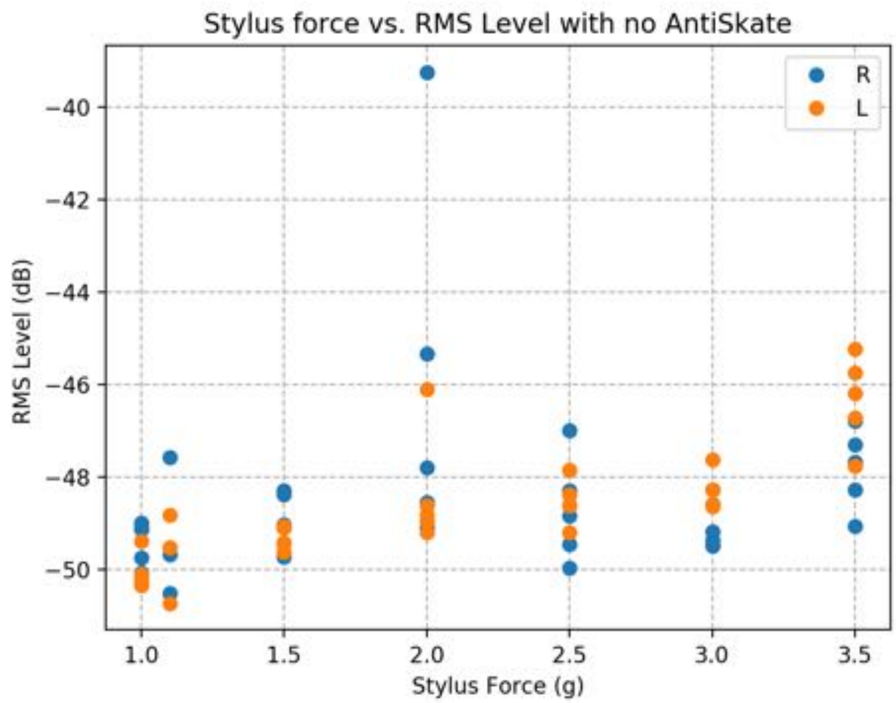


Figure 9: *An example in the variance in noise levels in a single groove of audio. Here the scatter in the data almost masks any trend in the data.*

Looking at the waveforms of audio being analyzed it was easy to see why. Although the same groove was being recorded for each measurement, the 2^{16} samples being analyzed and measured each time were offset.

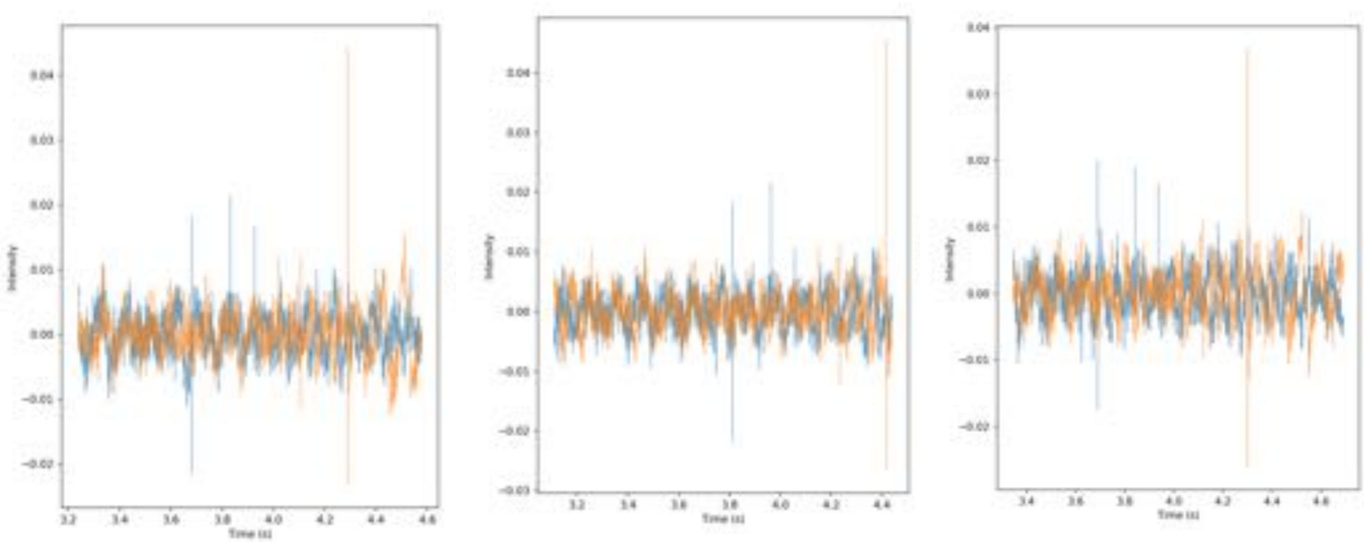


Figure 10: *Example waveforms of vinyl noise, where the colours represent the two audio channels. A loud click in the right (orange) channel is clearly visible in each waveform.*

A clever way we overcame this offset was to use the click present in the audio tracks right (orange) channel. These clicks are easily detectable and occur at precisely the same point on the record each recording. So simply searching for this click in the audio file and analyzing the 2^{16} samples after that click, ensures that we are measuring precisely the same spot of the groove with each recording.

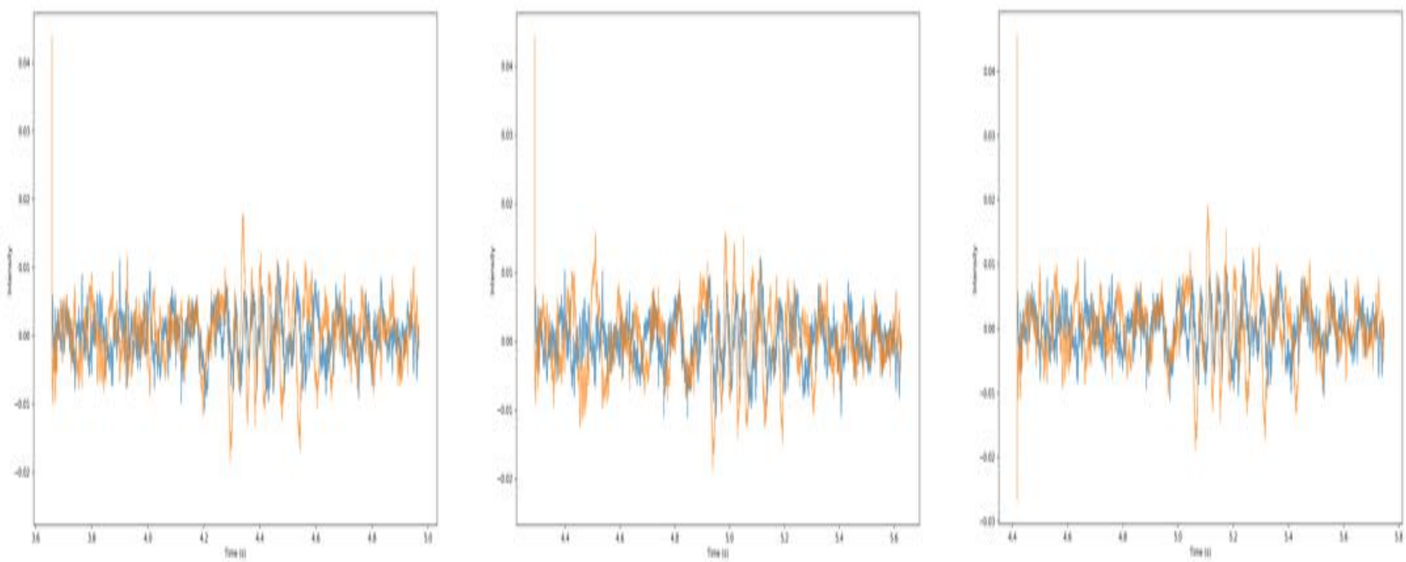


Figure 11: *An example of how the click can be used to line up multiple recordings of the same groove. These are the same audio files as in Figure 10.*

This greatly improved the precision of our measurements, and allowed us to make some qualitative observations about the nature of vinyl surface noise.

Using these techniques, several measurements were conducted. The first was on a vinyl record taken fresh off the press at Viryl. This record had never been played except for these tests, and had been manufactured weeks prior to these tests. The first tests used a quiet groove in approximately the centre of this record. This groove was recorded using various stylus forces and anti-skate adjustments in order to measure the effect that these forces have on the levels of surface noise.

For the second set of tests a selection of records of similar age and good condition all from the same publisher were recorded. These recordings were done using quiet grooves at different radii along these records, to measure the effect groove radius has on noise and look at how noise levels amongst a small set of vinyl records can vary.

Results

The first series of tests was to record the effect that stylus force has on the level of noise. This experiment was done twice: once with the anti-skating force turned off on the turntable and once with the anti-skate adjustments set to the manufacturers specification for that stylus force.

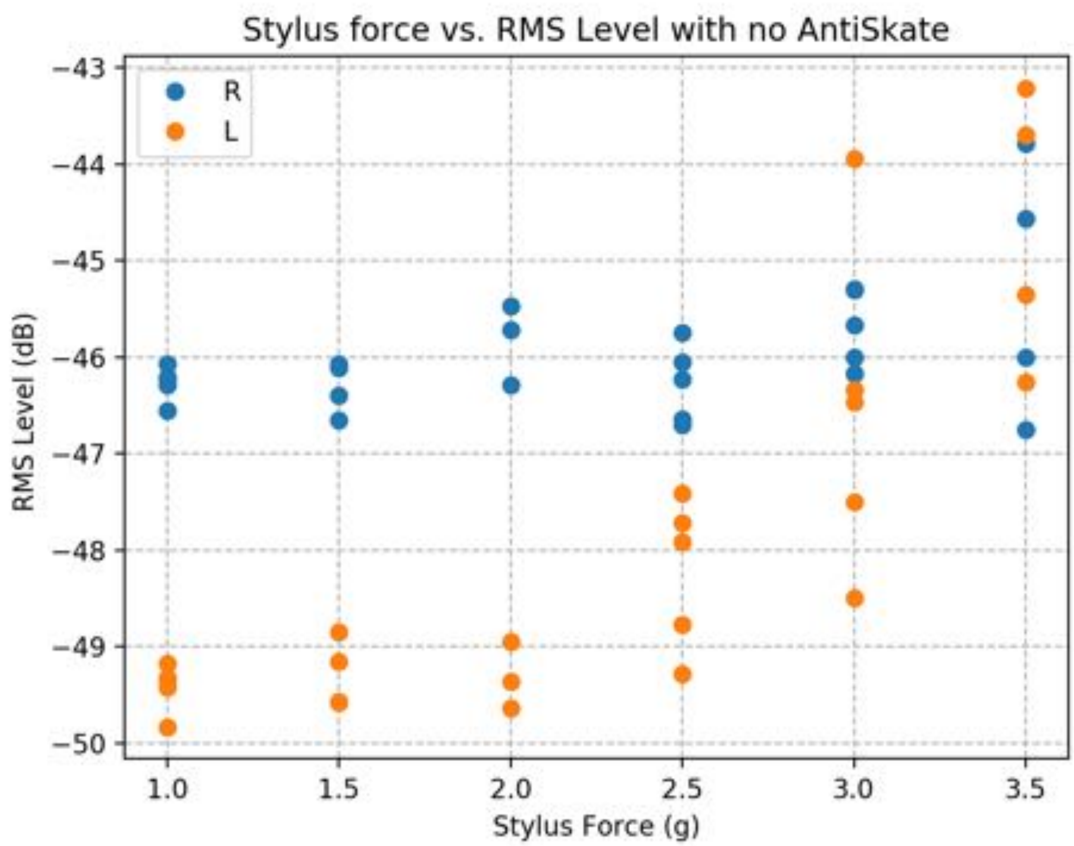


Figure 12: *RMS surface noise of a vinyl record as a function of stylus force, with the anti-skate mechanism of the turntable disengaged.*

The first results showed a rather surprising trend in the noise. The noise in the right channel, was roughly constant with respect to changing stylus force, and the noise in the left channel appeared to increase exponentially.

These measurements were then repeated with the anti-skate force being provided by the turntable. It's important to note that the anti-skate adjustments on the Technics turntable are a bit of a black box. The anti-skate force is set by a small dial beside the tonearm, with each increment on the dial meant to represent the appropriate anti-skate setting based on the stylus force being used. With no indication that the numbers on the anti-skate dial represent a particular unit. As such, measuring the skating force and anti-skating force would need to be done manually.

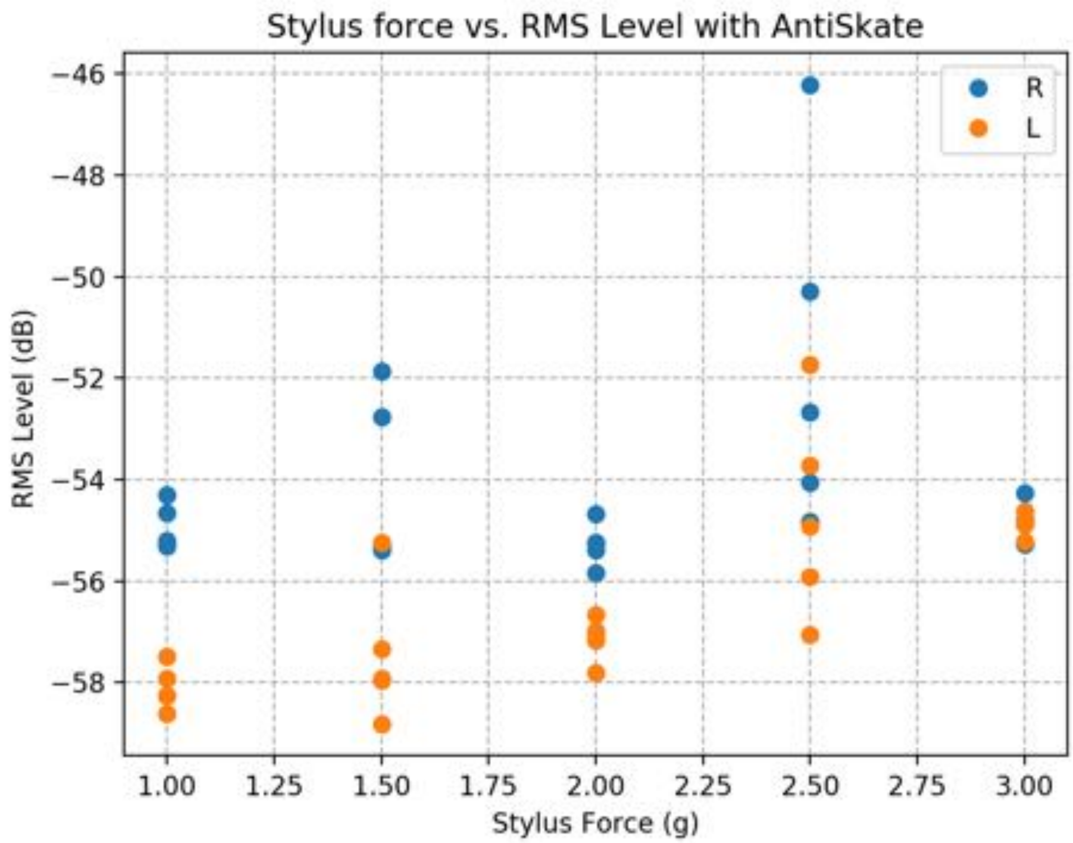


Figure 13: *RMS surface noise of a vinyl record as a function of stylus force, with the anti-skate mechanism of the turntable set to the manufacturers recommendation based on stylus force.*

Interestingly, with the anti-skating force engaged the relationship between stylus force and noise changes in a few notable ways. Firstly, overall the noise is much lower with the anti-skate engaged. The overall relationship for each channel stays roughly the same. The right channel remains roughly constant as a function of stylus force, while the left channel noise grows exponentially with stylus force—however at a shallow slope. As expected, the anti-skate adjustment balances the noise difference between the two stereo channels, with the noise in the two channels being balanced at maximum stylus force and anti-skate.

Lastly, a preliminary measurement was made keeping the stylus force constant and adjusting only the anti-skate.

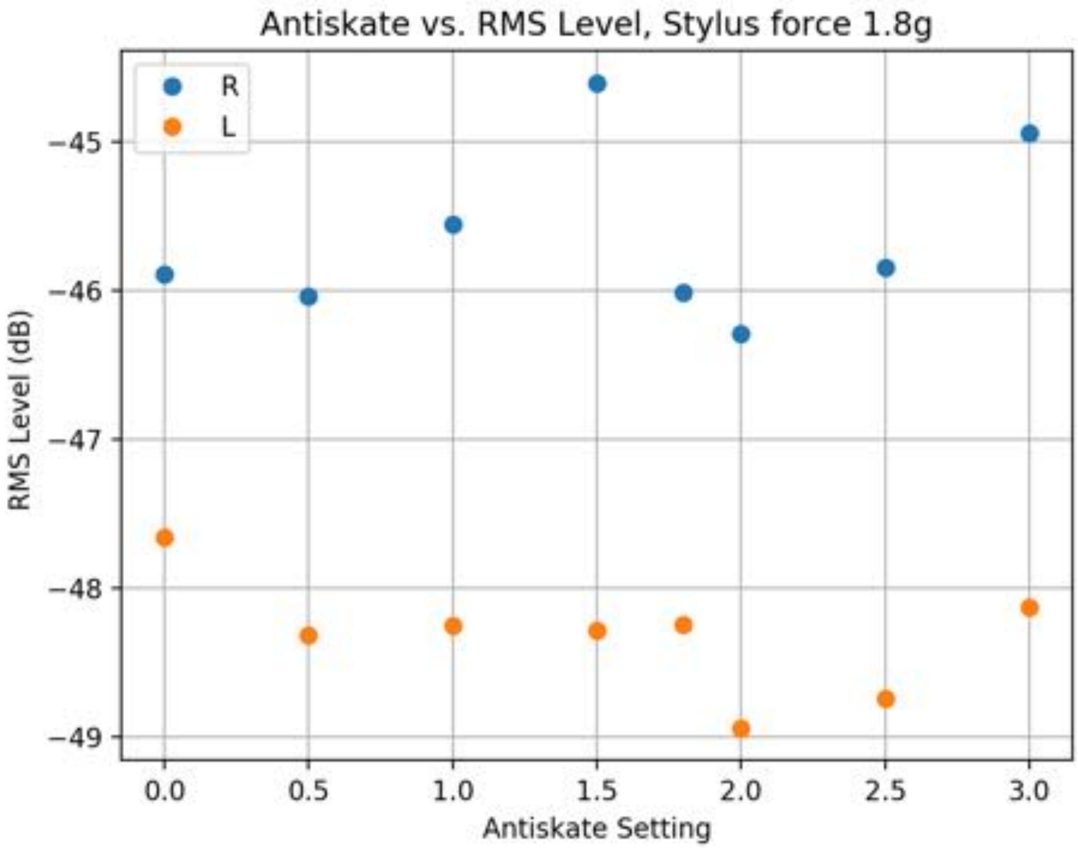


Figure 14: *A preliminary test done keeping stylus force constant and varying the anti-skate of the turntable.*

As this was a preliminary measurement, it's provided for informational purposes only. However, we do not expect

Next, in order to an effective measurement of radius several records needed to be used. This was also meant as a general survey of the noise of a selection of records available at the university. This data is presented in two different scatter plots, the first is the average of the noise in the two channels versus radius from the centre.

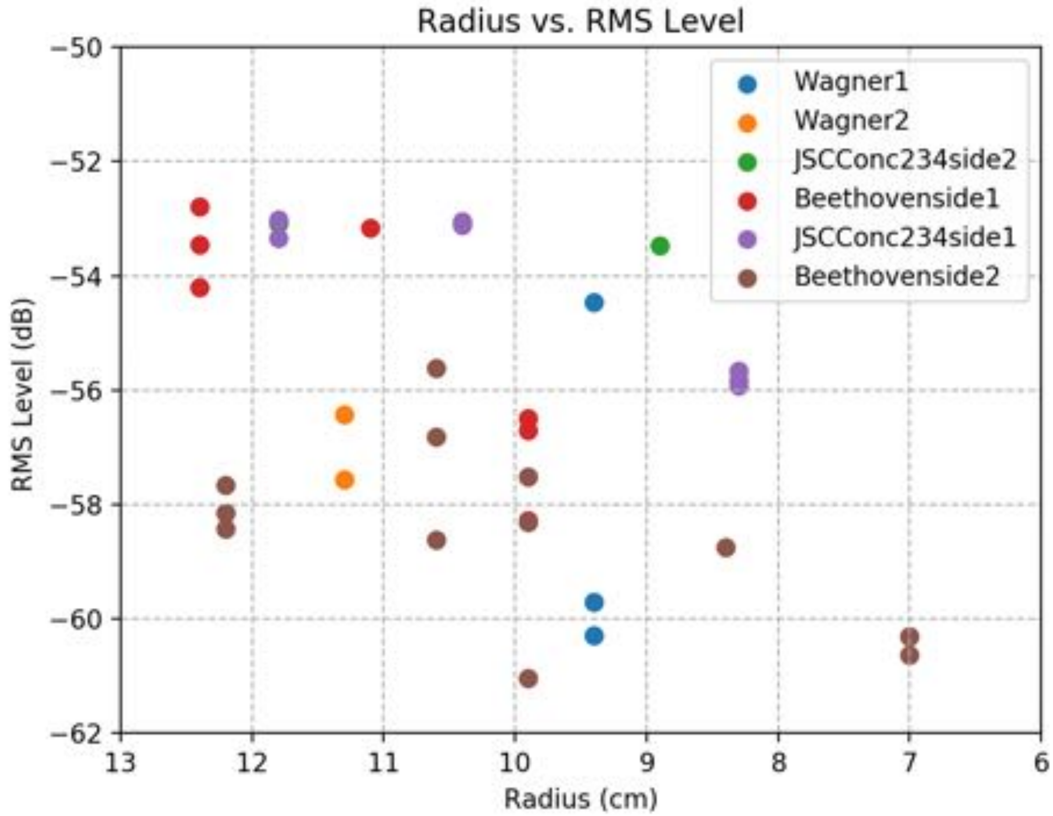


Figure 15: *RMS levels of noise, averaged between the L and R channels, of various records as a function of groove radius.*

Among the same records, the general trend of decreasing noise as the record plays is still visible. However, since each new radius was a completely different groove, the method of lining up clicks to increase the precision of our measurements could not be used. This causes a lot more scatter in the data, and makes the trend difficult to measure.

The second scatter plot shows the noise in the right channel vs left channel with the radius now corresponding to the size of the plot marker.

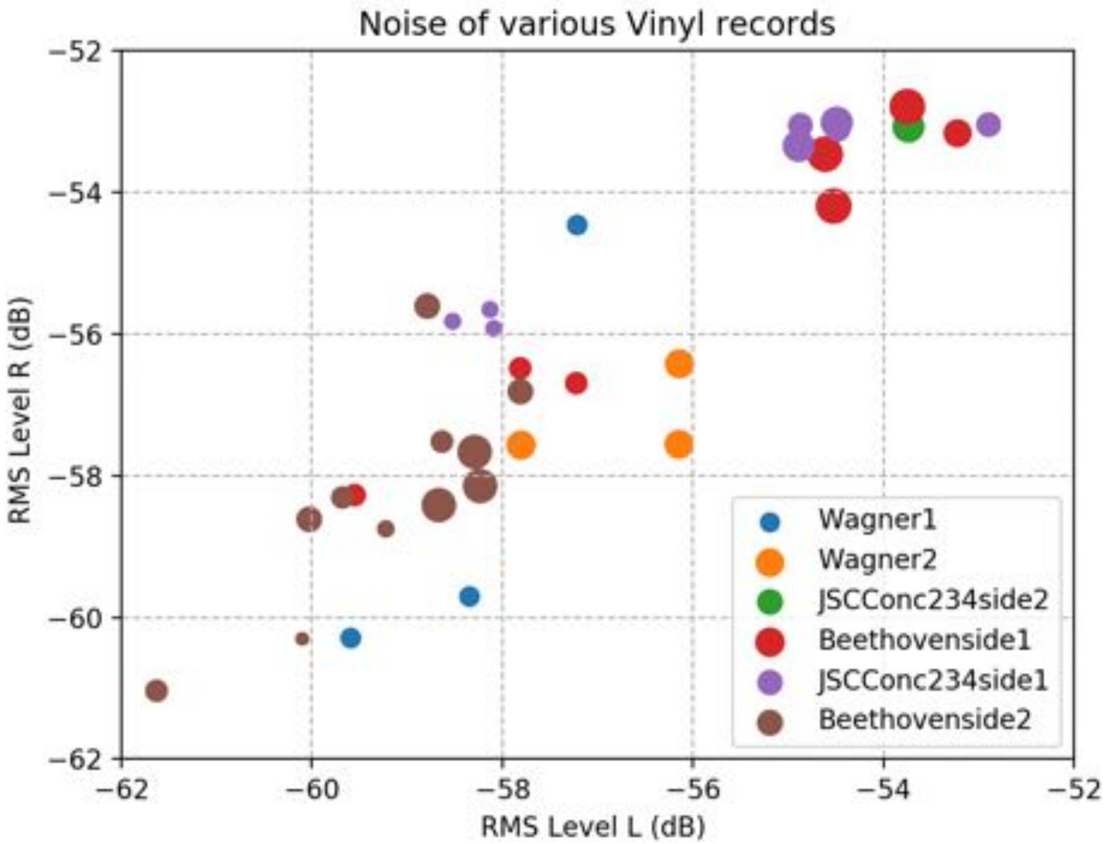


Figure 16: *RMS levels of noise of various records as a function of groove radius. The same data as Figure 15, shown differently. The size of the markers is determined by groove radius. Larger markers are grooves at a larger radius.*

Here as expected, the slope of the scatter is slightly greater than 45^{o} since there is generally more noise in the right channel. Amongst this data set the mean difference between the two channels was 1.03 dB, the maximum difference was 3.18 dB and minimum difference -0.203 dB, negative because the left channel was louder. Again, the general trend of larger radii having more noise is visible, especially amongst the same record.

In fact, looking at a single record in this sample, the Beethoven record side 2 for example, the trend of decreasing noise with radius is once again clearly shown.

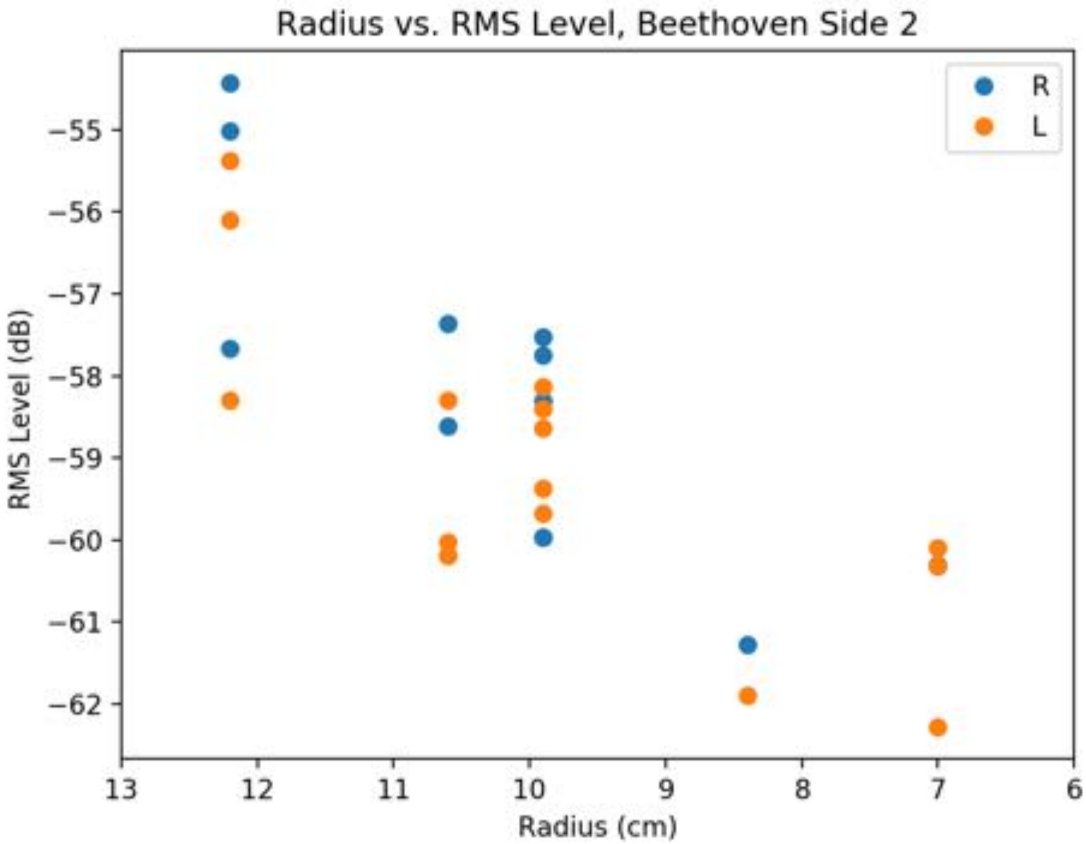


Figure 17: *Noise as a function of radius for a single record.*

However, without being able to line up clicks consistently there is a lot of spread in the data. As well, the difference between the left and right channels as a function of radius was also measured and showed no real trend.

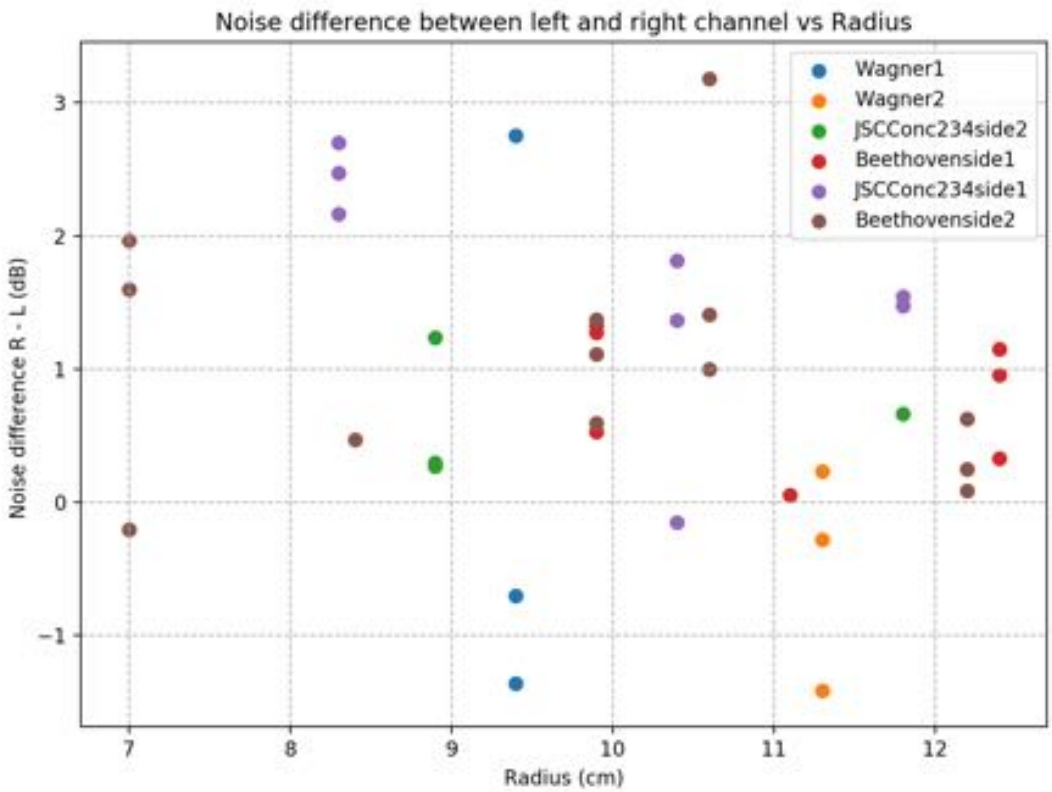


Figure 18: *Noise difference between the two channels as a function of radius for a single record.*

Discussion

The hypothesis being tested in this experiment was that the noise of a record was proportional to the force of friction between the stylus and the record, which itself was proportional to the forces exerted on the groove and the speed of the record underneath. From our testing of the record from Viryl, we found a strong correlation between stylus force and noise in the left channel both with and without the anti-skate enabled. This correlation was not seen in the right channel, where the noise was nearly constant with stylus force.

There is a noticeable effect that occurs at a stylus force of 2.5g. Here the noise measurements become rather inconsistent and spread out in both the channels, and the anti-skating force seemed to do little to balance this. One can only speculate as to what is going on in this case. One of the notable features in the spectrum of all the vinyl noise is a peak in the noise at around 10 Hz. This is believed to be the tonearm resonance of the turntable, however this has yet to be tested. Perhaps having the stylus force at 2.5g interacts with the tonearm at that force in a such a way that causes more noise and inconsistent tracking.

Interestingly, the least amount of noise was with the stylus force set to 1.0g and the anti-skate matched. However, the best performance arguable came from the stylus force maxed at 3.0g and the anti-skate matching that— which while it had more noise than 1.0g was the only measurement that balanced the noise in the two channels.

All records measured showed the same approximate relationship with noise and radius. However, one measurement that was difficult to make in this report but would be valuable is to see how the noise difference in the left and right channels evolve with radius and turntable speed independently. The Technics turntable allows for the record speed to be varied, however it lacks the controls to measure this speed absolutely. Future tests will involve a record containing sine tone of known frequency, thus the speed of the turntable platter could be easily calculated from the pitch shift in this sine wave.

This would lead to an updated hypothesis, that while the force of friction between the record and the stylus is definitely a factor in surface noise levels of vinyl—perhaps the system is more complicated than first thought. Where vinyl noise is based on the interaction between the tonearm More research into previous experiments and tests of turntable track-ability.

Lastly, error analysis for something such as noise is a rather difficult thing to do. In this experiment, we have done our best to minimize experimental errors with respect to taking our measurements, however there are ways to improve our analysis techniques so as to account for the variance in samples of noise. In fact, now that we have collected a sizeable number of recordings of vinyl noise more work should be done determine the statistical properties of these samples. What is the standard deviation in noise between grooves of the same vinyl records, between vinyl records or even with different samples of noise taken within the same groove. Understanding the statistical variance of all these properties and accounting for them is paramount to making any sorts of conclusions about vinyl noise. Specifically, with regards to our measurements with regards to stylus force, accounting for the "noise" in our data was done to great success, and developing similar techniques to other measurements will need to be done in order for future measurements to be as meaningful.

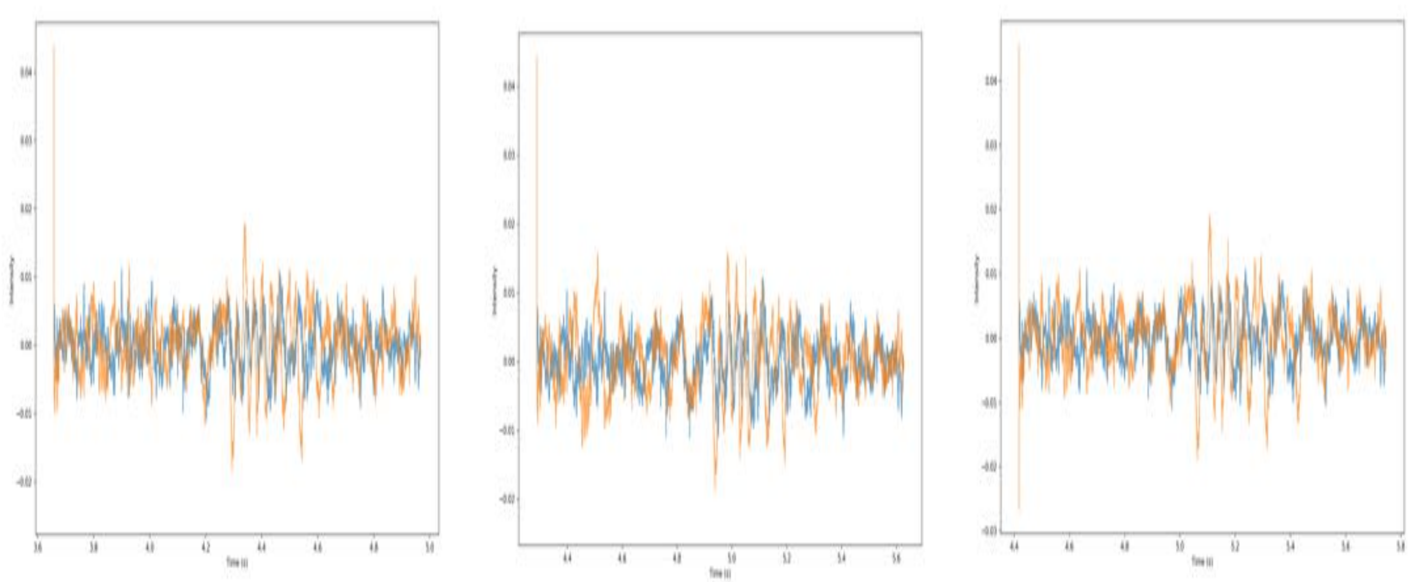
Concluding Remarks

A more detailed look at the effect that speed of the record would prove very useful to vinyl manufacturers. A few sources claim that the skating force is not proportional with record speed or groove radius [7], however testing whether noise is proportional to speed and groove radius would resolve whether the increased level of surface noise near the edge of the record is caused by the physics of the playback system, or due to there simply being more noise in the record itself near the edges.

Following the hypothesis that noise on a vinyl record are caused by small imperfections in the vinyl surface, it may be possible to measure these imperfections from the audio recordings. In the previous report, a Shure TTR-103 test record was used to normalize some of the recordings. This record contained grooves cut in such a way to ensure the stylus moves at a certain peak velocity when played back. Taking noise measurements using this normalization method, would allow us to relate how much the stylus is moving with the levels of noise.

A similar reasoning would allow us to measure the size of the imperfections that cause "clicks" to be heard. An ancillary measurement made during these recordings showed that the clicks we've observed fit the characteristics of tiny imperfections in a groove wall, as they seem to occur exclusively in one channel. Thus, recording a record using a very high sample rate, say 192 kHz, could give a scale to these imperfections and how much they perturb the stylus.

The technique we used to ensure that we are measuring the same section of the groove each recording, allows us to make some more qualitative observations into the nature of vinyl noise. Looking at the waveforms of the audio files measured in the stylus force tests, the same features are present in all the wave forms. Looking again at the waveforms in *Figure 11:*



In addition to the click present in the right channel, the basic shape of the waveform is identical in all of the recordings of this groove. This lends itself to the idea that surface noise on a vinyl record is the result of imperfections on the surface of the record itself. As every time the stylus passes over this particular groove, it is moved in a similar way. Comparing these waveforms of the same groove recorded over multiple trials would help distinguish between what features of vinyl noise are characteristic of the record, and what are truly random.

As well, a basic flaw in these measurements is that the noise was measured in quiet grooves of a vinyl records. In the future, if a vinyl record with a known signal is used for testing then the signal to noise could be measured while audio is being played by the turntable. As of now our system has not tested how the noise changes as the stylus tracks a system. However, we have no reason to assume that the noise will not change, measurements of noise while the record is playing audio will be much more conclusive and indicative of noise during audio playback.

Acknowledgements

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Viryl Technologies provided some of the equipment for measurement and some of their expertise in ensuring the apparatus and turntable used for recording was set up correctly. James Hashmi, CTO of Viryl, was the main contact at Viryl. Doug Chappell set up the turntable used in this project.

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