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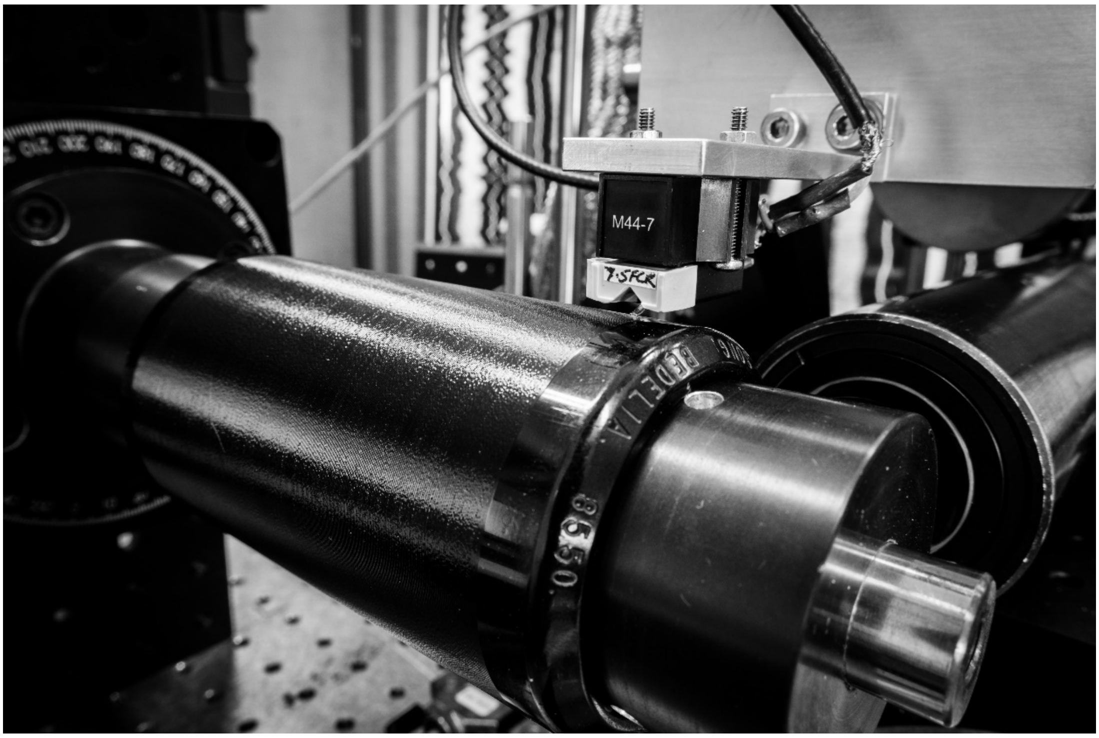

Study of Wear and Degradation on Sound Recordings

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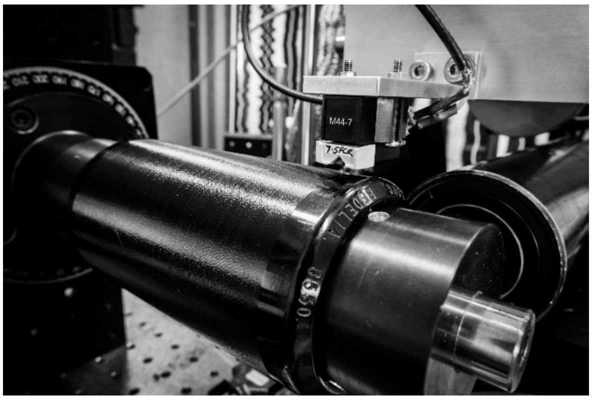
Abstract

At Lawrence Berkeley National Laboratory, Carl Haber and his team have been involved in the audio reconstruction of old records. They developed optical scanners to digitize the surface and play the record virtually. This solution is great for fragile or damaged medias. Some simpler instruments used for the audio restoration are mechanical phonographs. There was always a debate in the field about the wearing introduce by such phonograph.

The goal of this project was to build a phonograph and study the wearing and damage caused by the instrument. The phonograph uses a tonearm with a phono cartridge that tracks the groove using a linear stage.

Some image analysis tools were also developed to be able to align and compare images of the cylinder's surface and evaluate the wearing



between playbacks.

The phonograph deliver a good audio quality but no obvious traces of wearing were discovered after just one playback. A reasonable amount of playbacks is needed to start to damage the surface of the record.

This project served as a starting point to really understand the complex interaction between the stylus and the record's surface.

Acknowledgement

I would like to thank Carl Haber for his help and advices during this project. He shares his knowledges with me during this project and feedback when writing the report. I also would like to thank Earl Cornell for his explanations and help when using the IRENE platform and all the software around it. I want to give thanks to Peter Alyea from the Library of Congress for his advices and expertise about wax cylinder playbacks and help. My thanks also to Cory Lee who machined all the pieces for the phonograph.

I would like to thank Eric Fragnière, Ottar Johnsen and Luciano Sbaiz for their supervision. Their help was more than valuable, particularly their knowledges about audio records playback and signal processing.

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Contents

1 Introduction

1.1 Context

One of the first media used to record sound was the wax cylinder. This support was used on a phonograph where the vibration of a diaphragm cut a groove in the wax surface. When playing the record with a stylus on the groove it was possible to reproduce the recorded sound with quality. One of the biggest problem with wax is that the material is soft and wear easily while being played back with a stylus who applied a relatively big pressure. This wearing effect degrade the sound quality.

For many years, a team supervised by Carl Haber has been involved in the audio reconstruction of old records at the Lawrence Berkeley National Laboratory. They have been mainly focused on cylinders and discs records, which are too fragile to be read by a conventional phonograph.

In order to retrieve the audio from these records, methods and instruments were developed by the team to scan optically records and play them virtually. This technique gives the opportunity to recover the audio from really fragile or even damage records. In the case of audio restoration of wax cylinders, two different techniques are used today. One uses a mechanical phonograph (the commercially available *Archeophone* for example) to play the record with a stylus and the other one uses an optical scan of the record and some image processing. The first method is of course quicker but the second one does not physically interact with the cylinder and may deliver better quality.

With these two methods, emerge a debate in the audio restoration field about the degradation of the record when the audio of this one is restore with a mechanical phonograph. Previous work on the effects of mechanical playback have left open some questions on methodology and systematics and therefore the results have been difficult to understand. Here we attempt to address this subject again with clarity.

1.2 Project objectives

The objectives of this project is to measure and evaluate the wearing of a wax cylinder and figure out its effect on the sound record. By knowing the effect of the wearing, it would be possible to limit the damages or even correct this degradation and achieve a better sound quality with a proper algorithm for example. This project only focuses on wax cylinder records.

The first step is to study interactions between the stylus and a wax cylinder to evaluate the possible effects. Then a mechanical phonograph needs to be built in order to be able to realistically wear the cylinder while getting the audio with the phono cartridge.

A new method needs to be developed in order to evaluate the level of wearing. This method should use different techniques to evaluate the degradation of the cylinder. One technique is to observe the audio spectrum of the playback and analyze the changes. Another one is to evaluate the surface texture change in the groove elevation. In order to achieve it, a comparison software written in C# needs to be coded to compare two images of the surface and measure the difference between them. This software will need to be able to properly register two images in order to compare them.

Once these methods are working, a big part of the project is simply to perform a lot of playbacks and gather some data to compare the cylinder after this mechanical stress.

1.3 Planning

The planning of this project can be found at the end of the Appendix section.

1.4 Organization of the report

This report is divided in three main different parts. The first one will talk about the wax cylinder and the existing methods of non-invasive recordings reading. It will give a small summary of the history of wax cylinder and then explain its limitations. Knowing the records medium properties is the key to understand how wearing affects the audio.

The second part is about the building of a phonograph using a phono cartridge to play cylinders and record the audio while wearing it. This part also describe the software and other tools and methods developed to analyze the state of wearing.

The last part consists of the wearing test itself and the analysis of the result. Some explanation about the observed effects will also take place. Finally, a personal overview and the conclusion of this project will be exposed at the end of this document.

1.5 Folder organization

The folder organization works as follows:

- Publication	
o Admin	Administrative documents
o Presentations	Presentations done during the project
o Report	Final version of the report and flyers
o Weekly report	Weekly reports, minutes and logbook
- Documentation	External documentation
- SW_ImageRegistration	
o Code	Source code
o Test images	Images used to test the software
- Wearing tests	Scan and audio files gathered during tests

This last folder is explained in detail in the appendices 11.1.

2 Concept

2.1 History

Over the last 150 years, humans always wanted to record sound. Many different methods have been invented. Nowadays most of the sound that we listen come from a digital media but the earliest known methods were called acoustical recordings. The Frenchman Edouard-Léon Scott de Martinville invented the first machine, which was able to record sound in 1857. At that time, this machine was used to study the visual shape of the sound waves because it was not possible to play back those recordings.

Thomas Edison invented about 20 years after the first device capable of both recording and reproducing sounds. It was the birth of the phonograph. The sound itself was recorded on a cylinder covered with a soft material such as tinfoil or wax. The cutter, which vibrates through the diaphragm, shapes a groove on the surface of the medium. By replacing the cutter with a stylus, it becomes possible to play the record. These cylindrical records are easy to use but their great disadvantage is that they are hard to store and take up a lot of space. The vertical modulation is also more subject to tracing errors, which cut off frequencies above 3-4 kHz.

Figure 1: Edison cylinder phonograph, circa 1899, courtesy of Wikipedia

A new device called the gramophone solved this problem. Instead of carving the groove on a cylinder, a disc was used. These records were easy to reproduce by simply creating a negative mold of the master and then pressing new discs. The audio quality was also as good as or even better than the cylinder.

With the raise of the electronic microphone and vacuum tubes marked a big step towards in the quality improvement. For the first time it was possible to easily amplify the audio which enable a bigger signal over noise ratio and deliver accurate results with discs.

The last big step in the audio recording fields was the introduction of magnetic recordings. This method pushed the boundaries in term of audio quality and the possible recording duration. Later the compact disc had a great commercial life because of his small size and ease of production. Nowadays physical support tend to slowly disappear because sounds is consumed online or stored among other files on hard drives or solid state storage solutions. The study of this project will be done on the early wax cylinders.

2.2 Wax cylinder

In the early days of sound recording, the first support was the wax cylinder. This medium was the first one to be “easily” available. To record sound, a virgin cylinder was placed in a recording lathe and the vibration of the sound displaces a diaphragm attached to a cutter, which carves a groove. To play it back, the cylinder was mounted in a phonograph and a stylus sitting in the groove vibrate while the cylinder spin. This vibration was then carried to a diaphragm who create the sound. Sometimes phonograph had both cutting and playing head to be able to perform both operations with the same machine.

2.2.1 Groove geometry

On a wax cylinder the groove ride along the cylinder forming a spiral with a very fine pitch. Instead of having a V-shape groove like a vinyl record for example, wax cylinder are record with a cylindrical cutter. Therefore, the groove has a round shallow profile. [1]

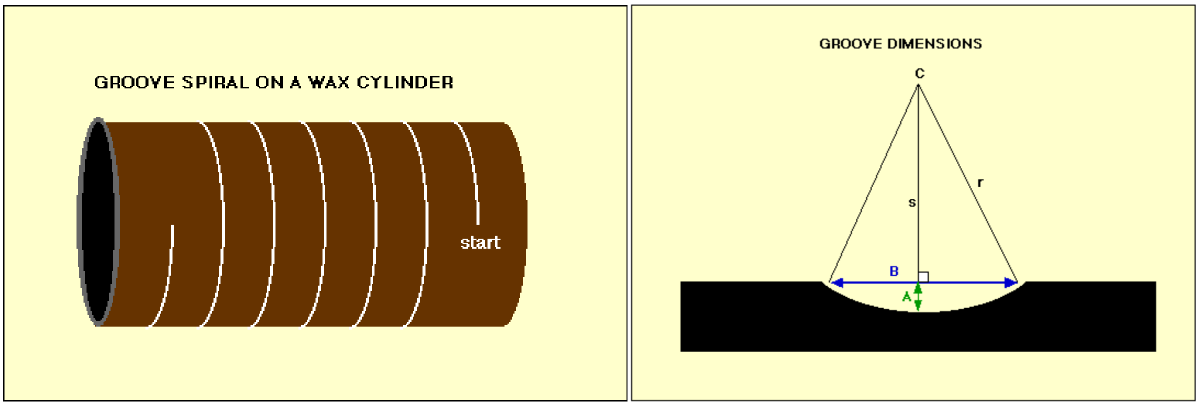


Figure 2: Groove spiral and geometry of a wax cylinder, courtesy of POPPY Records [2]

The following table summarize the main dimensions for both type of cylinders: the 2-minute and 4-minute cylinder. In this project, only 2-minute cylinders are used.

Type of cylinder	2-minute cylinder	4-minute cylinder
Cylinder dimensions	Circa 2 3/16” x 4” (circa 55 x 102 mm)	
Rotation speed	100-160 rpm	
Thread pitch	100 TPI (254 µm)	200 TPI (127 µm)
Maximum width of the groove (B)	254 µm	127 µm
Depth of the cut groove (A)	5-20 µm	

2.2.2 Groove modulation

Unlike most common disc records where the groove is modulated horizontally, the groove on the wax cylinder is modulated vertically. The audio waveform is proportional to the derivative of the surface shape so the highest amplitude is where the surface is most steep.

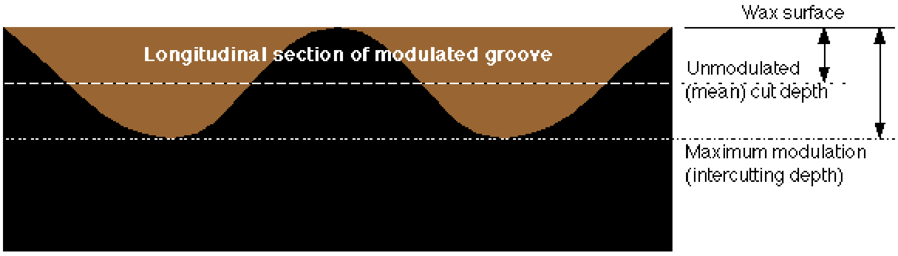


Figure 3: Side view of the groove of a wax cylinder, courtesy of POPPY Records

The leading groove, which contains no sound information, is cut down to the unmodulated cut depth. Then the cutter swing around this depth to record the audio information.

2.2.3 Different cylinder's waxes

The first cylinders used in the history were formed with a cardboard tube, which was coated with a thin layer of wax to record sound. These cylinders were easy to use and produced a good sound but the wax was very brittle and it was not easy to do copy of the cylinder. These cylinders were known as "Brown wax cylinder" which, sometimes, wore in as few as twenty playbacks.

In 1900, Thomas B Lambert patented a celluloid cylinder, which was harder than the classic wax cylinder. For the first time it was possible to reproduce records. These cylinders were known as "indestructible" because they would not shatter after a fall. Two years later as a response to the "indestructible" cylinder, Edison Records launched the "Edison Gold Molded Records" which uses some black hard wax. They were molded from a master cylinder and they were harder and less prompt to wearing.

A couple of year after Edison launched the "Blue Amberol" cylinder which used a hard wax but with a smaller pitch to be able to record up to 4 minutes. He later acquired Lambert's patent and created a celluloid cylinder named "Edison Blue Amberol Records" with a plaster core and a thin coat of celluloid.

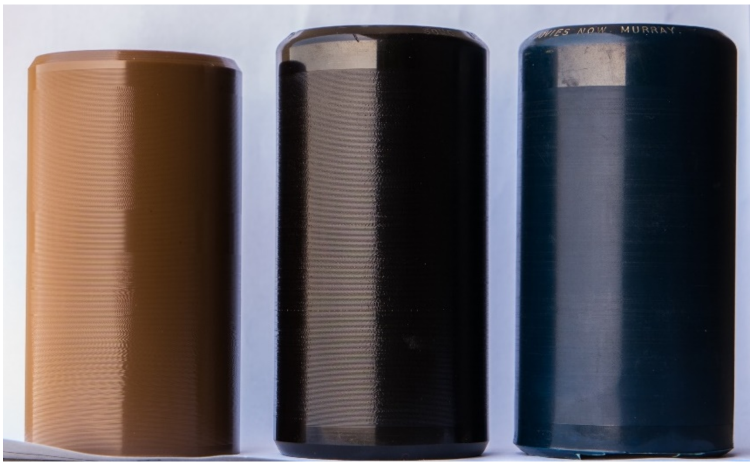


Figure 4: Three main types of cylinders: brown soft wax, black hard wax and blue Amberol celluloid cylinders

In the case of this study, only soft brown wax cylinders will be used. Cylinders blank are made by "Paul Morris's Music" in the UK using his own wax recipe. This wax uses a mix of sodium and aluminum salts of stearic acid, excess free acid and some soft wax. The stearic acid (the main component) is widely used to make church candle therefore, the final wax is relatively similar. First the stearic acid and caustic soda (sodium hydroxide: NaOH) are molten together (saponification) to literally get soap. Aluminum is dissolved in a caustic soda solution (aluminum salt) and then mixed with the soap solution. The resulting mass is a soft wax known as “metallic soap” wax. [7]

It is hard to get some physical properties (yield strength for example) of the resulting wax and there is no available data about it. The best way would be to do some physical tests with a wax sample.

2.2.4 Frequency response

Wax cylinders have two limitations of the frequency response. The first come from the cutting because the cutter is angled compare to the surface. Therefore, when the frequency and the amplitude of the signal are high, the backside of the cutter could touch the slope of the groove. It limits the slew rate of the signal and the amplitude should be smaller pass a certain frequency.

The second limitation is met when the cylinder is played. When the valley of the groove is too narrow for the tip of the stylus to fit the amplitude decrease. This effect is known as a tracing error and was already studied in 1940 by W. Lewis and F. Hunt. This limitation is easily describe with the following image:

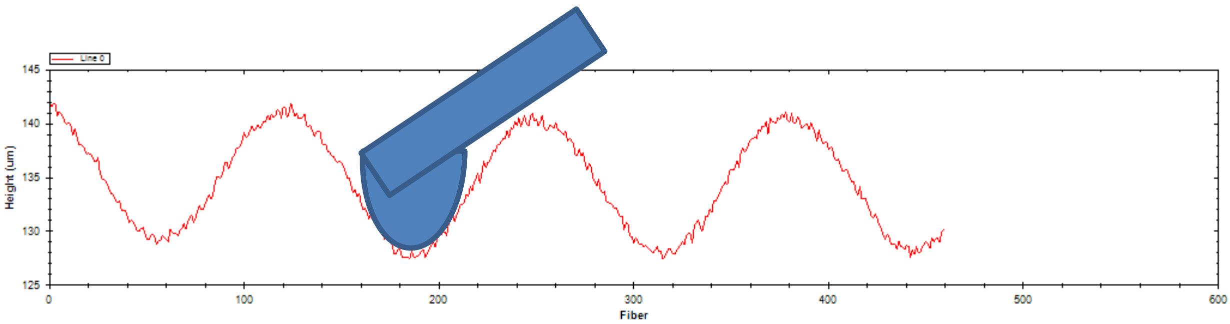


Figure 5: Frequency limit for the stylus

Generally, the audio level for frequencies under 1 kHz is limited by the amplitude and for frequencies over 1 kHz by the slew rate. At around 4-5 kHz the maximum amplitude decrease because of the size of the stylus. The dimension of the tip could also introduce some distortions at higher frequencies because the stylus would not be able to reproduce the bottom of the groove but will not have problem with the top of the groove. In this case the sinewave will be distorted. [3] [4]

2.2.5 Tests cylinders used in this project

To perform some wearing tests it was important to have some good quality test cylinders with clear specifications. It would be very hard to do meaningful measurements on a cylinder with music for example. POPPY Records provided the test cylinders. This English company uses some soft wax blank cylinders manufactured by Paul Morris Music also in the UK to cut test patterns.

The CXP003 calibration cylinder is a standard 2 minutes cylinder with a 100 TPI groove pitch and a 160-rpm running speed. The record contains three different tracks. The first one is a 45 seconds 1 kHz tone followed by a 15 seconds silence. The third track is a 65 seconds long frequency sweep from 5 kHz down to 50 Hz. The accuracy of the amplitude of the sweep is ± 2 dB. The sweep is interrupted with 0.5-second silence at the following frequencies: 3 kHz, 2 kHz, 1 kHz, 500 Hz, 300 Hz, 200 Hz and 100 Hz.

Figure 6: Picture of the brown wax test cylinder

Two cylinder were purchased and one was kept as a control cylinder (B) and the other one was used to do some wearing tests (A).

2.2.6 Stylus used in this project

The phono cartridge used to play the cylinder is a standard Shure M44-7 cartridge but with a stylus shaped for wax cylinders. The stylus has a sapphire spherical tip with a 15 mil diameter (or 380 µm).

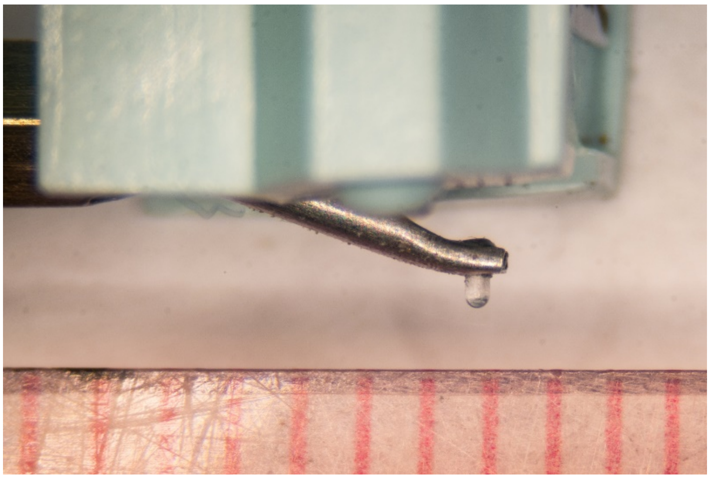


Figure 7: Spherical stylus tip (1 mm graduation)

2.3 Description of a phonograph

The phonograph is a mechanical machine designed to play a cylinder and reproduce the recorded audio. The first one was hand powered with a flywheel and a simple speed indicator to let the user correct his speed. Later phonographs will use hand-cranked spring motor.

The principle is relatively straightforward. The cylinder is mounted on the mandrel and the rotation of the cylinder synchronizes the rotation of a leadscrew. This leadscrew displaces the carriage along the cylinder. The pitch is given by the gear ratio between the cylinder and the leadscrew. Finally, the carriage has a stylus that sits in the groove and vibrates a diaphragm accordingly to the groove depth. Because this system is strictly mechanical, the pressure on the stylus was high to achieve a reasonable sound level. The pressure was around 60 g, which explain why cylinders were quickly damaged.

Figure 8: Edison's cylinder phonograph, courtesy of Majestic Record

The mandrel in the middle support the cylinder and the round diaphragm is visible on the front. The leadscrew is in the back with the gear train on the left to synchronize both rotations.

3 Existing system

3.1 Overview

The existing system for sound reconstruction uses a confocal probe to get a 3D scan of the complete surface of the cylinder. The workflow to reproduce the audio out of a cylinder is described below.

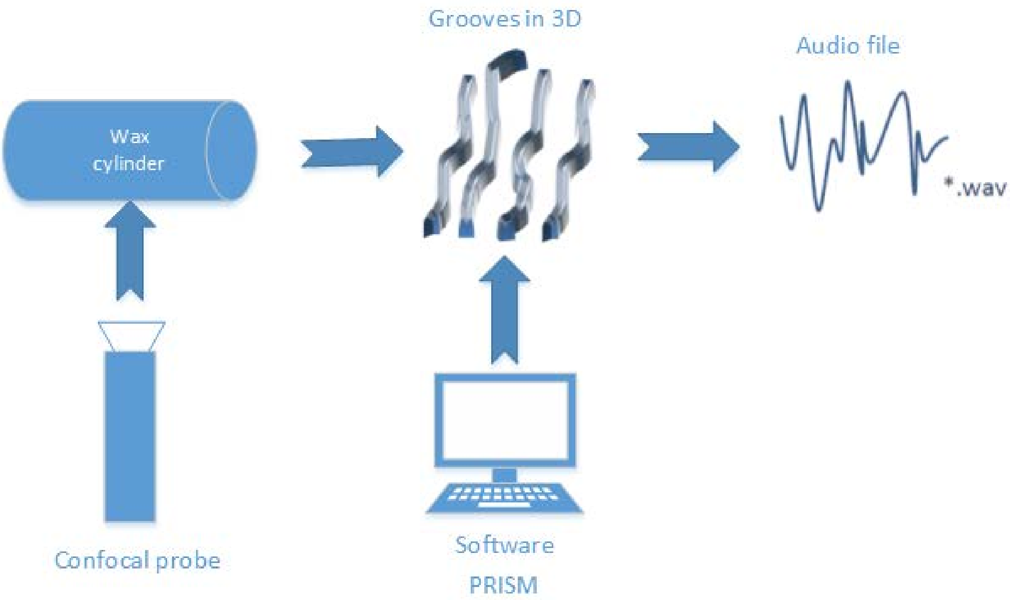


Figure 9: Workflow for wax cylinder audio reconstruction

The first step of this process is to scan the complete surface of the cylinder. The cylinder is mounted on a rotary stage and the confocal probe on a linear one. The probe return the elevation of each point and by rotating the cylinder it is possible to scan it by slices. The complete scan is in the form of a grayscale images with the elevation of the surface as the intensity.

The next step is executed with the PRISM software. This software will stitches and process all the slices. It also remove every blobs caused by dust particles or wrong measured points. Finally, the 3D groove is played with a virtual stylus to reproduce the audio. The result is a clean audio file of the recorded sound.

The LBNL also as a similar setup to scan disc but this one uses a camera to image the surface. A 2D image of the surface is enough to be able to reproduce the record. The process is similar but quicker. During this project, only the 3D setup will be used.

3.2 IRENE hardware

The complete IRENE setup is mounted on a vibration-damped table with all the electronic under it. The hearth of the system is the confocal probe which measure the depth of the groove to get a 3D images of the cylinder's surface. This probe as a very small range of measure therefore an auto focus solution is needed. The solution is provide with the Keyence laser distance sensor which measures continuously the distance to the cylinder and correct the distance between the probe and the cylinder to stay in range. The cylinder is mounted on the mandrel, which spins, and the linear stage is used to move the probe along the cylinder to image it completely.

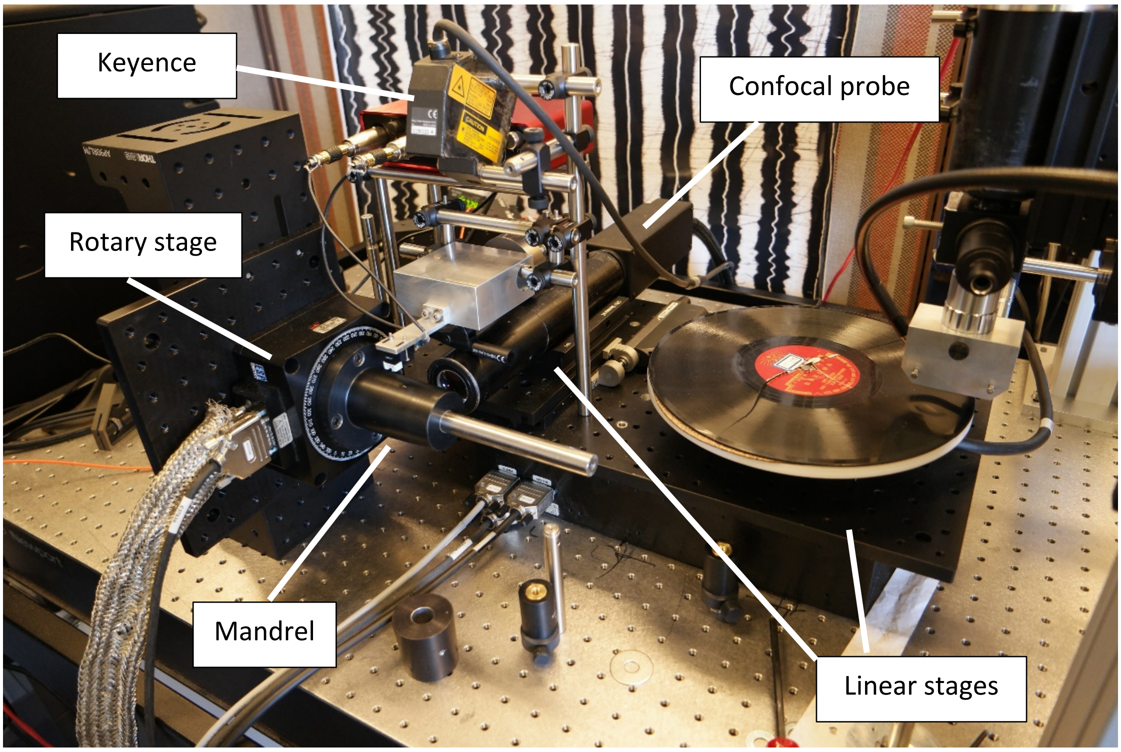


Figure 10: IRENE setup

3.2.1 Confocal probe

A confocal probe take advantage of chromatic aberrations of the reflected light on a surface. A spectrometer analyze the light and the distance is proportional with the wavelength of the reflected light. This technique offer a good resolution (under 50 nm) for a decent range (around 300 µm).

The lab uses a MPLS180 system from Stil. This probe is able to scan a line with 180 points (1.8 mm with 10 µm between each point). In this study, the cylinder was scanned with 48'000 samples per revolution (49'200 with an overlap of 9°. One slice: 369°) which give a sampling frequency of:

$$f_s = \frac{n_{samples}}{t_{revolution}} = \frac{n_{samples}}{\frac{1}{\omega_{revolution}}} = n_{samples} \cdot \omega_{revolution} = n \cdot \frac{v}{60} = 48'000 \cdot \frac{160\ rpm}{60} = 128\ kHz$$

With a Nyquist frequency of 64 kHz, the measurement method has a good margin for this audio application.

3.2.2 Stages

To rotate the cylinder a Newport RGV100BL rotary stage is used. This stage rotates up to 720°/s but the configuration file was changed during the project to go up to 960°/s to match the speed of the cylinder. This change enables a louder audio level and a more realistic constraint for the cylinder.

The linear stage used to move the probe is a XML210 from Newport too. The host computer, which runs the acquisition program, controlled both stages via a Newport XPS driver over Ethernet.

Figure 11: RGV100BL Rotary stage, courtesy of Newport

Figure 12: XML210 Linear stage, courtesy of Newport

Travel range	360° (continuous)
Maximum speed	720°/s (override at 960°/s)
Load capacity	100 N
Accuracy	± 0.005°
Repeatability	± 0.00055°

Travel range	210 mm
Maximum speed	300 mm/s
Load capacity	300 N
Accuracy	± 1.5 µm
Repeatability	± 0.04 µm

3.3 Scan acquisition

A host computer runs a Lab View workbench called “3D-Control-MPLS-fZ” that controls all the stages and the optical probe. This program has a couple of built-in macros to automate certain functions. It is possible to take the dark reference for the probe. The “Find Z” function is used to automatically adjust the probe position to have the groove in the small range of the probe. A real time viewer of the surface is also available. The following image shows the GUI of this Lab View VI.

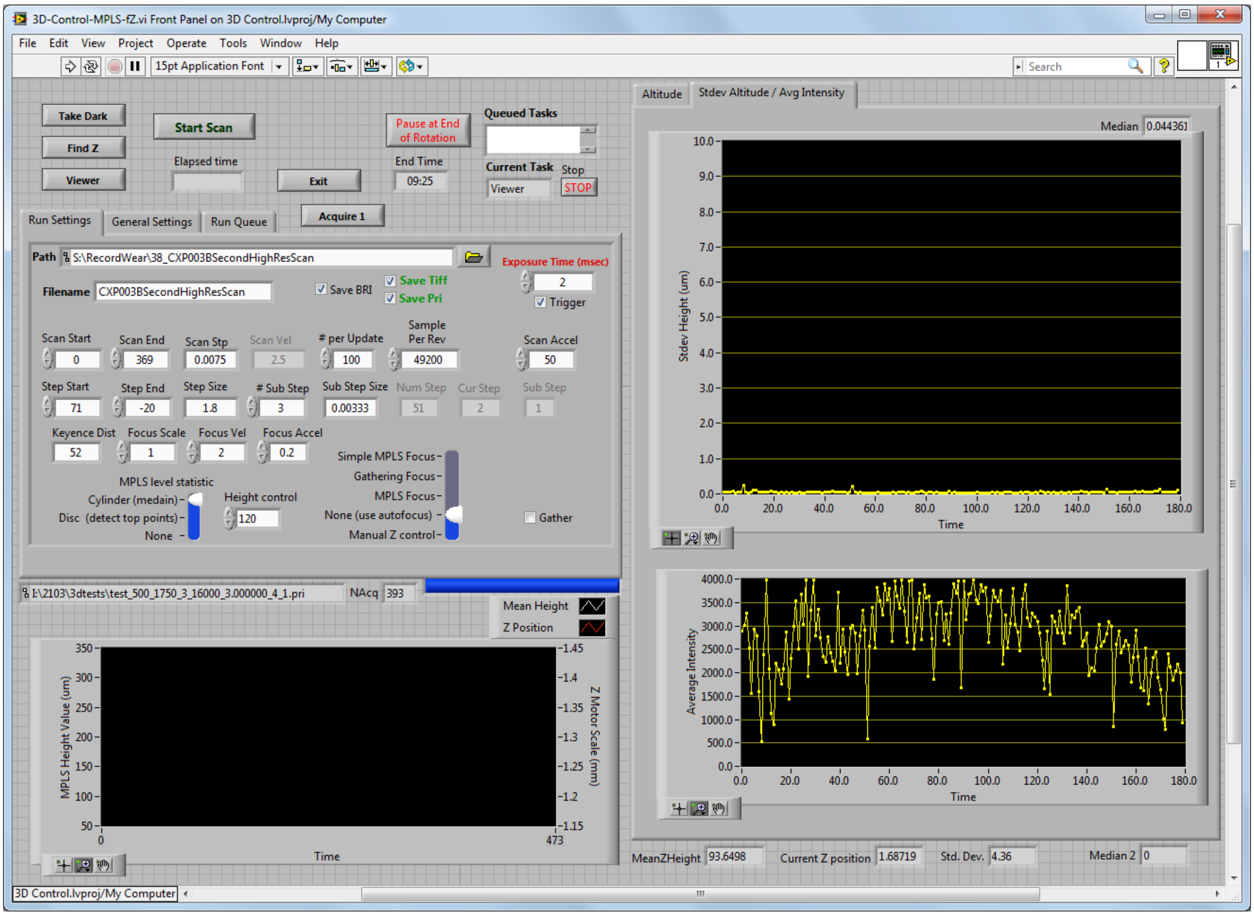


Figure 13: Scan acquisition program interface

The main settings of this program are the following ones:

- The path and the filename for the scan
- "Scan Start" and "Scan End", in this case from 0° to 369° to have a small overlap.
- "Sample per Rev", in this case 48'000 + 1'200 (9°/360° × 48'000) samples.
- "Step Start" and "Step End" are the position of the start and the end of the cylinder.

Once all the parameters are written it is time to take the dark, find the correct distance with the probe and finally launch the scan.

This second useful program is called "I xps" and offers the possibility to manually move each axis. This software also lets to slave one axis with another one. This is used in this project to slave the tracking of the groove with the rotation of the cylinder. The following equation calculates the ratio between both stages:

$$ratio = \frac{cylinder\ pitch}{360°} = \frac{254\ \mu m}{360°} = 0.000705554\ mm/°$$

For a 200 TPI cylinder, this value is 0.000352777 mm/°. This ratio should be negative for the stage to move in the right direction (CW rotation and linear stage from the motor to the end of the mandrel).

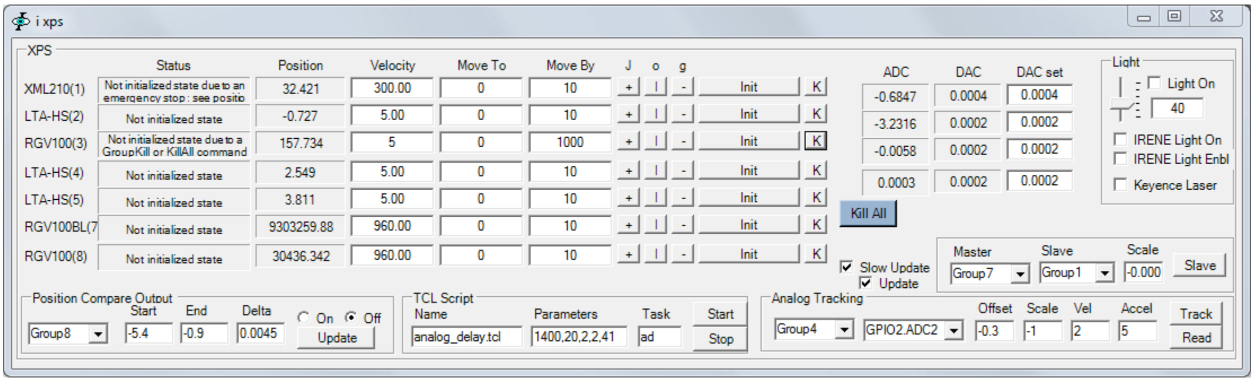


Figure 14: Stages control program

All the values in these two programs are in millimeters and degrees.

3.4 Prism Software

Prism is a software used to stitch all the scan slices together in a complete cylinder image. Then the blobs on the image are cleaned and the 3D groove is played with a virtual stylus to reproduce the audio.

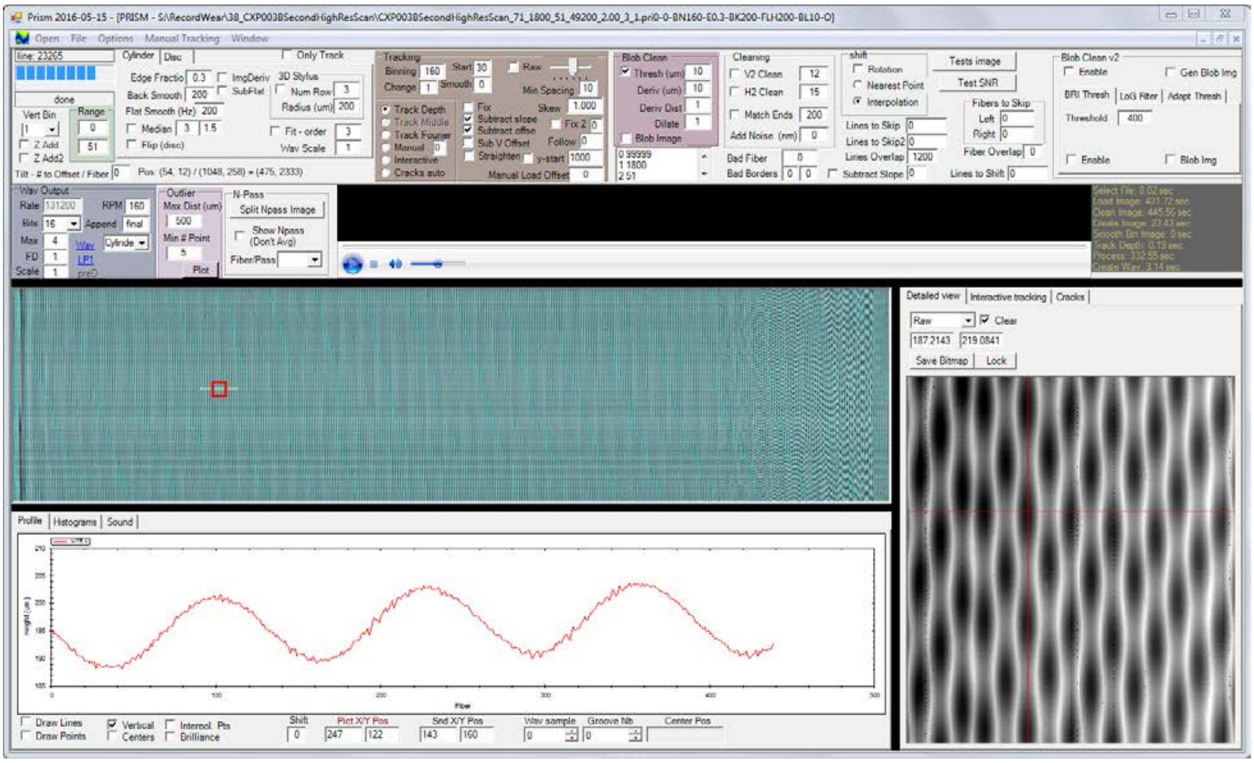


Figure 15: PRISM software

The top part of the software contains all the different settings. On the left is the range of the scan file, which contains all the slices the program will stitch together. One another important setting is the blobs cleaning. In this case, with a filter of 10 µm the cleaning is relatively soft.

4 Development of a phonograph

In order to wear mechanically a wax cylinder a phonograph was needed. The goal is not to achieve the best audio quality possible but with a good phonograph, the wearing would be heaven more realistic. Therefore, the idea was to reach ideally the same quality as the optical probe.

4.1 First prototype with passive tracking

The original idea was to build a passive phonograph with the stylus tracking the groove. A shaft parallel with the cylinder would be used to let the tonearm travelling along the cylinder while maintaining the cartridge on the groove. The tonearm used two Teflon (PTFE) bearings to ride smoothly on the shaft. Teflon bearings have a little more friction than ball bearings but they offer smoother translation. Ball bearings could introduce some vibration that the stylus could pick-up. The tonearm uses a counterweight to balance the phono cartridge and apply a precise and tunable pressure on the stylus.

The following left image shows the drawing for this passive phonograph. The right image is the physical version. The top vertical support was designed to use a confocal probe to perform some static measurements of the needle penetration.

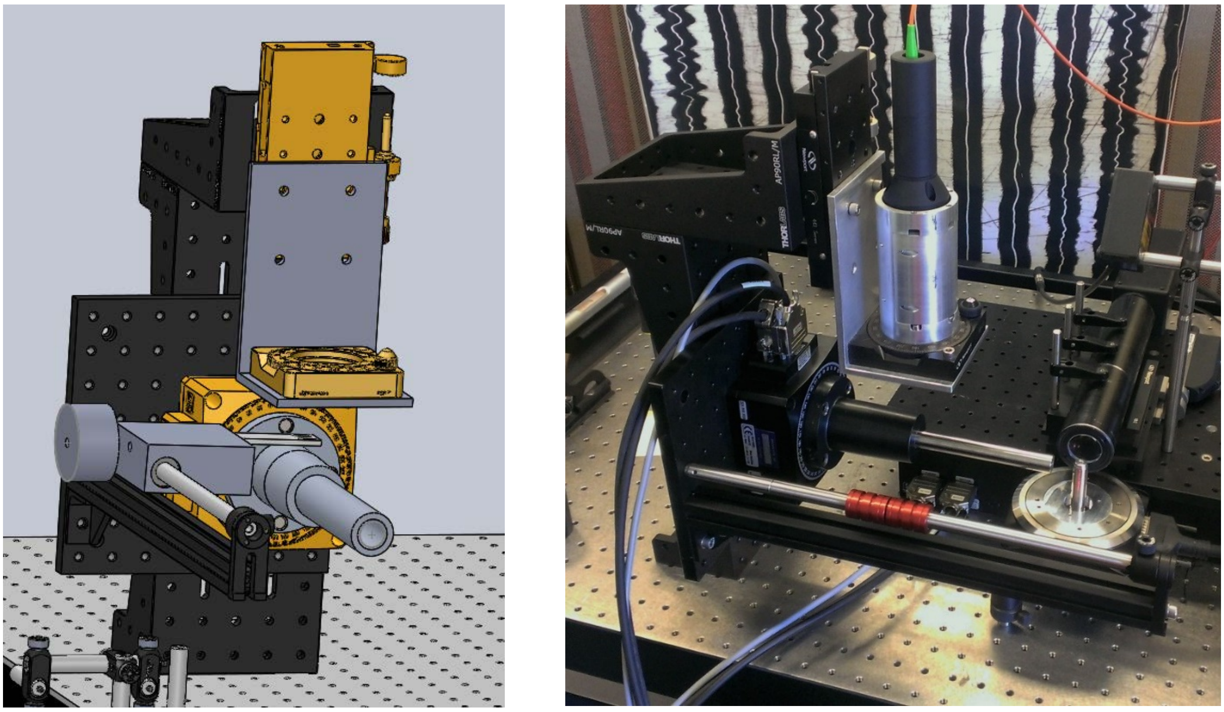


Figure 16: CAD drawing of the first phonograph and the build on the right with the red linear bearings

This architecture did not work because with the round shape of the groove, the tracking force is really small and was not enough to fight the friction of the tonearm.

Because of the two circular shapes, the tangent to the point of contact has an acute angle. This small angle produces a small resulting horizontal tracking force. The principle is illustrated in the drawing bellow.

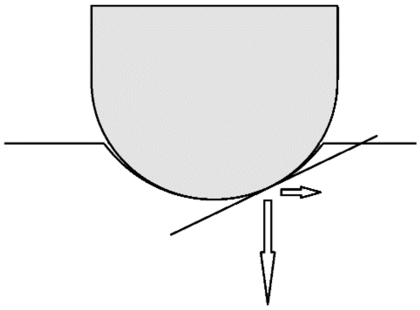


Figure 17: Stylus sitting in the groove with the different forces

The small pressure on the stylus (around 2 g or 20 mN) is not enough to be able to move a tonearm.

4.2 Second iteration with active tracking

The second version of the phonograph balances the tonearm on a single pivot point. A linear stage, which is slaved, with the rotary stage tracks the groove.

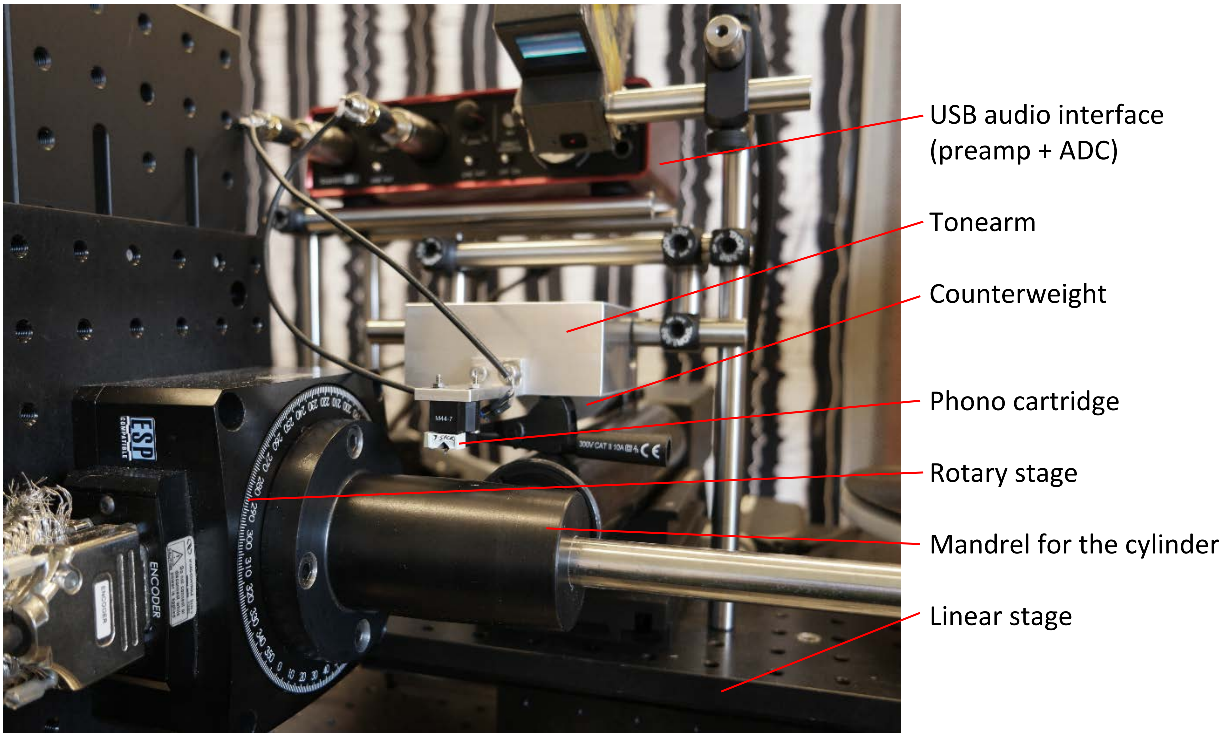


Figure 18: Active tracking phonograph

The first playbacks were made using a CTP1000 preamp and an M-Audio Audiophile 2496 soundcard. The problem with this setup was that the sound card had a 22.1 kHz low-pass filter and it was impossible to change it when using a 96 kHz sampling frequency. The preamp and the soundcard were later replaced by a *Focusrite Scarlett 2i2* audio interface. This device is connected over USB with the computer and offers sampling frequencies up to 96 kHz with a 24 bits resolution. The characteristic of the anti-aliasing filter is also nicer with a clear breakdown at the Nyquist frequency.

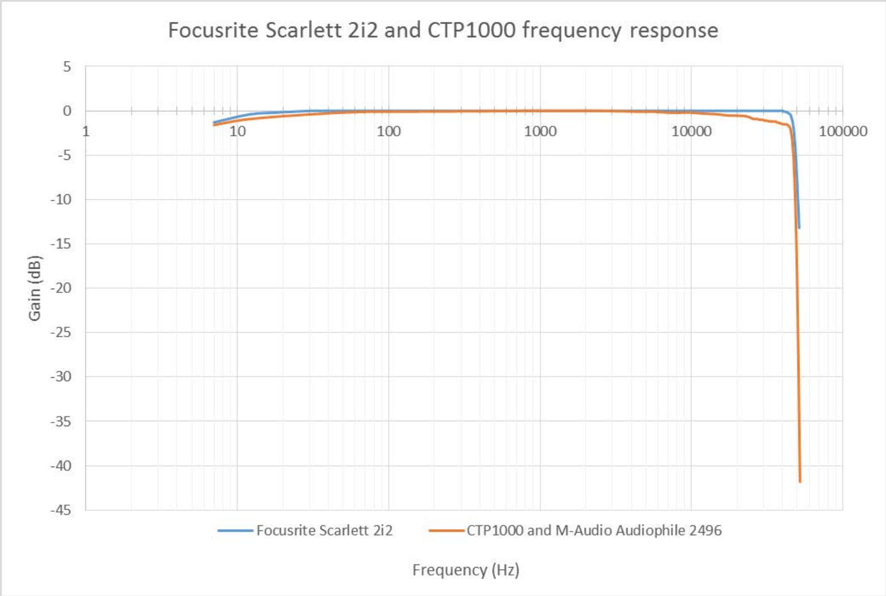


Figure 19: Frequency response of the Focusrite Scarlett 2i2 and the CTP1000 + Audiophile 2496 soundcard

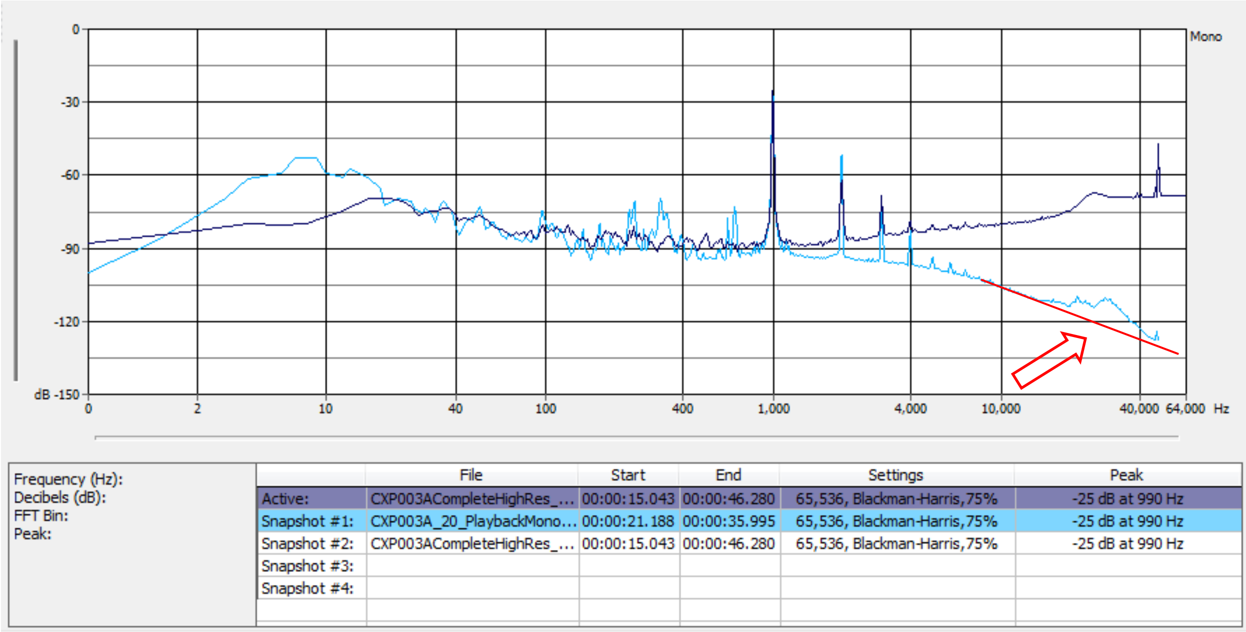
The frequency response of the soundcard was made after the whole electronic was changed. Surprisingly the cut off frequency was now correct. But the *Scarlett 2i2* has still a better response.

4.3 Comparison between optical and mechanical playback

To judge the quality of the phonograph, it is interesting to compare a mechanical playback with an optical one, which is use as a reference.

4.3.1 Observed differences

The following figure shows the spectrum of the 1 kHz tone of the test cylinder with the optical probe and the mechanical phonograph. The darker blue spectrum is the optical playback. Both signals are aligned to get the same amplitude for the 1 kHz peak. The two spectrums are relatively similar but a couple of characteristics are visible. First, the noise floor of the stylus playback is lower around 1 kHz and three peaks are visible between 200 and 800 Hz. Finally, the first overtone is also bigger with the stylus, which shows a bigger distortion of the tone. The frequency response of the cylinder is clearly visible. The spectrum starts to fall off after 4 kHz. However, instead of being a nice slope the stylus was still able to get the surface texture of the cylinder. The small bumps around 22 kHz is visible on the optical playback spectrum and this texture is visible on the stylus playback too. This confirms that the stylus is able to reproduce these higher frequencies but with significant attenuation.



The total harmonic distortion of both signals could also be calculated to evaluate the difference with the following equation [6]:

$$THD_{\%} = 100 \cdot \sqrt{\frac{{V_2}^2 + {V_3}^2 + \cdots + {V_n}^2}{V_1}}$$

With V_n as the amplitude in volt of each harmonic. The first harmonic is the fundamental tone. Generally, five harmonics are enough to get a decent value. The audio level can be converted from dB to volt with the following formula [7]:

$$V_n = V_0 \cdot 10^{\frac{L_n}{20}} \; with \; V_0 = 1 \; \equiv 0 \; dB \; (reference\; factor)$$

The following table give the distortion for both the optical probe and the stylus. The optical system does not introduce any distortion so this distortion comes from the cylinder itself. The stylus playback just adds 1.3 % of distortion. The result is still relatively good.

	Optical probe		Stylus	
Harmonic	Level (dB)	Level (V)	Level (dB)	Level (V)
1	-26	5.01E-02	-18	1.26E-01
2	-60	1.00E-03	-44	6.31E-03
3	-67	4.47E-04	-58	1.26E-03
4	-80	1.00E-04	-70	3.16E-04
5	-82	7.94E-05	-82	7.94E-05
THD(%)		0.49		1.82

Figure 20: Total harmonic distortion of an optical or mechanical playback

From the specifications, the Scarlett 2i2 has a distortion of <0.002%. This value is negligible in the result.

4.3.2 Phonograph's noise

After doing some playback with the stylus some strange peaks appear between 200 and 800 Hz. These peaks are not visible in the audio spectrum coming from the optical probe scan. Moreover, these peaks are present during the whole record. The part showed here was the 1 kHz tone. In this case, there should not be any peaks under 1 kHz. The three interesting peaks are illustrated bellow.

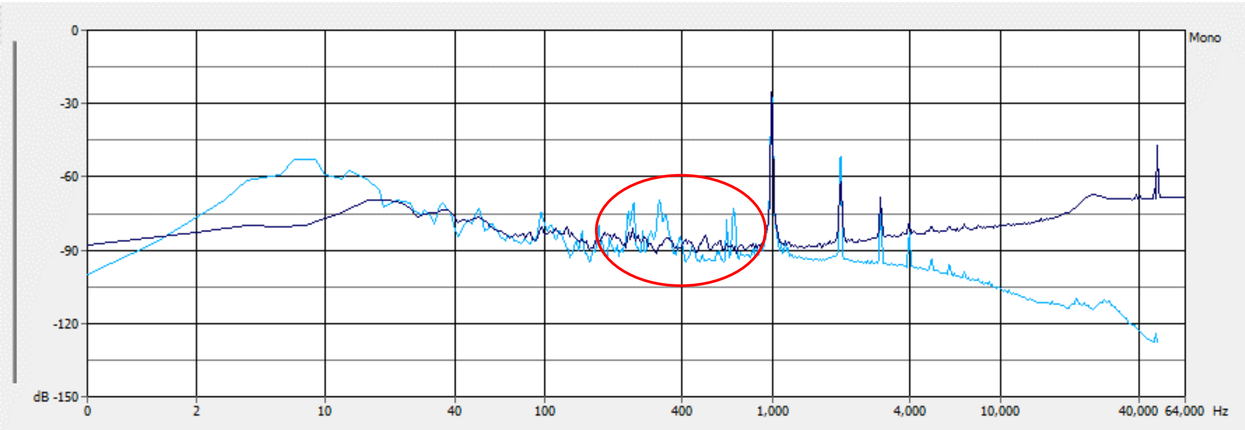


Figure 21: Noise peaks on the audio spectrum

To find the origin of this noise, a first test was performed with the stylus not in contact with the surface. This test resulted in a perfectly flat spectrum and gave a noise baseline. The second test was down with the rotary stage spinning at different speeds. The stylus was still standing in the air at 80 mm of the rotary stage. All the recorded audio was then shrunk to match the original speed of the cylinder (960°/s).

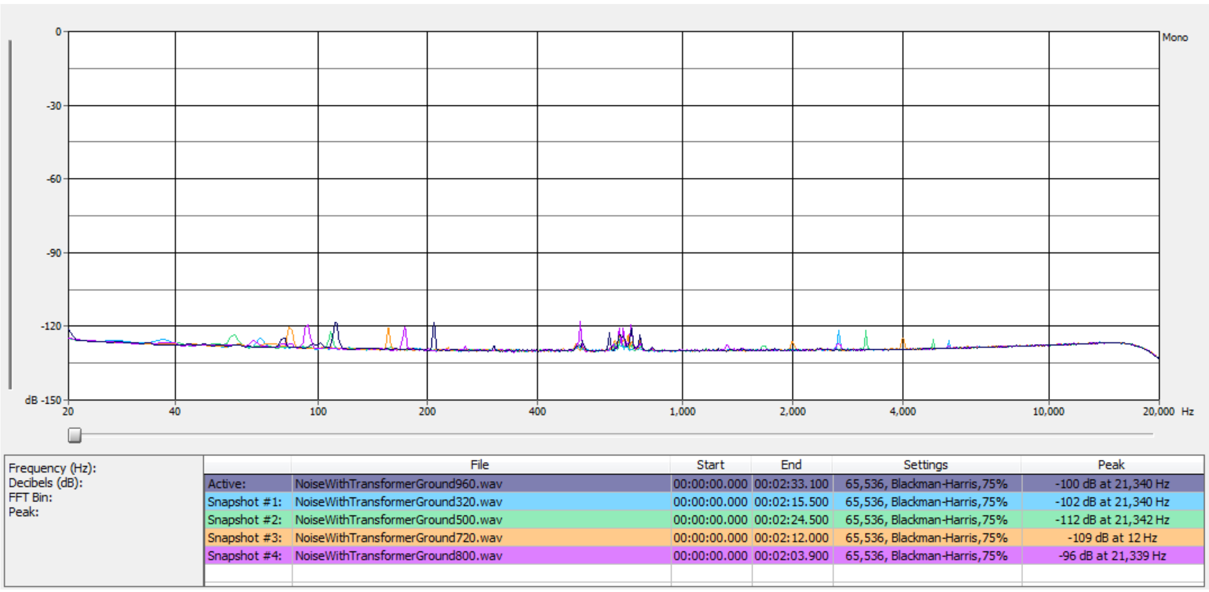


Figure 22: Noise peaks with the rotary stage spinning

There is clearly two different behaviors in the noise. Some peaks stay at the same place and the other ones shift. At around 800 Hz all the peaks stayed at the same frequency. That means the noise source is related to the speed of the rotary stage. There is also two sets of peaks at around 110 Hz and 207 Hz. The second one is not an overtone of the first one because the frequency is not exactly the double. This noise come from an external source because it has a constant frequency as it shifts differently with the rotation speed. There is also some peaks of noise in the higher frequencies.

One of the origin of the peak that does not move (800 Hz) could come from the rotary stage bearings. It is not possible to determine a precise frequency because there is not an available reference for the stage's bearings. We can see in the following table that these specific frequencies are between 2 and 15 times the rotation speed. The rotary stage spin at 160 rpm therefore frequencies are between 320 Hz and 2.4 kHz.

Fault	Abbreviation	Equation	Range
Fundamental train frequency	FTF	$\frac{S}{2} \times \left[1 - \left(\frac{Bd}{Pd} \times \cos\theta\right)\right]$	< ½ S
Ball spin frequency	BSF	$\frac{Pd}{2Bd} \times S \times \left[1 - \left(\frac{Bd}{Pd} \times \cos\theta\right)^2\right]$	5-15 × S
Ball pass frequency (outer race)	BPFO	$\frac{Nb}{2} \times S \times \left[1 - \left(\frac{Bd}{Pd} \times \cos\theta\right)\right]$	2-15 × S
Ball pass frequency (inner race)	BPFI	$\frac{Nb}{2} \times S \times \left[1 + \left(\frac{Bd}{Pd} \times \cos\theta\right)\right]$	4-15 × S
Where: Nb = Number of rolling elements, Bd = Ball (or roller) diameter	Pd = Pitch diameter, S = Shaft speed	θ = Contact angle	

Figure 23: Table with different ball bearings defects frequencies [5]

This explanation is plausible but a test was carried on with a different stage to see if this peak was still there and it is the case. The frequency is also similar. It is a little bit strange that both stages have the same frequency signature!

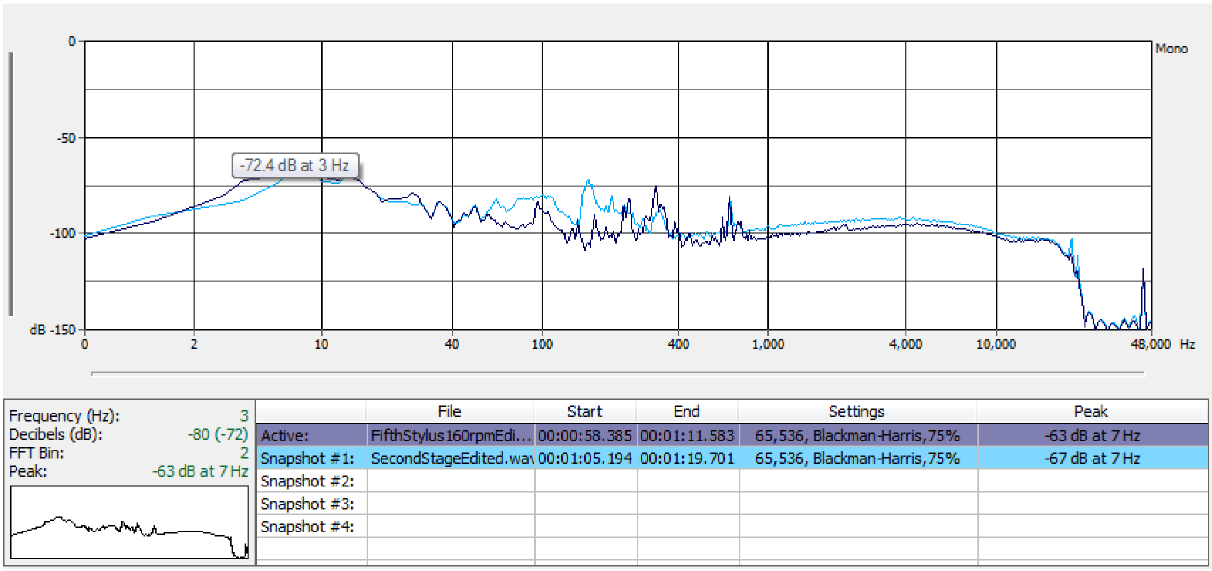


Figure 24; Same cylinder but with different rotary stage

The blue signal is a playback with a different rotary stage. It is not very visible on the graphic but the peak at 678 Hz stays at the same place.

The others noise peaks are electrical noise. A couple of different solutions were tested and most of the perturbations were coming from the cable between the phono cartridge and the preamp. In fact the voltage and the current of the signal is so low that it is easily disrupted. The best result was with this cable shielded. Then the preamp and the soundcard were changed with an USB audio interface which contains both a preamp and a digitizer. With this solution, the cables are shorter and the noise was attenuated by 6 dB.

The other source of noise could come from the ground. The driver for the stages is injecting some leakage current in the ground and this current could introduce some perturbations. A simple isolation transformer was used to isolate the driver from the rest of the electronic. This solution helped by attenuating the peaks of 4-5 dB but the problem is still there. A transformer with a power conditioning filter/circuit was tested but it could not handle the required power usage.

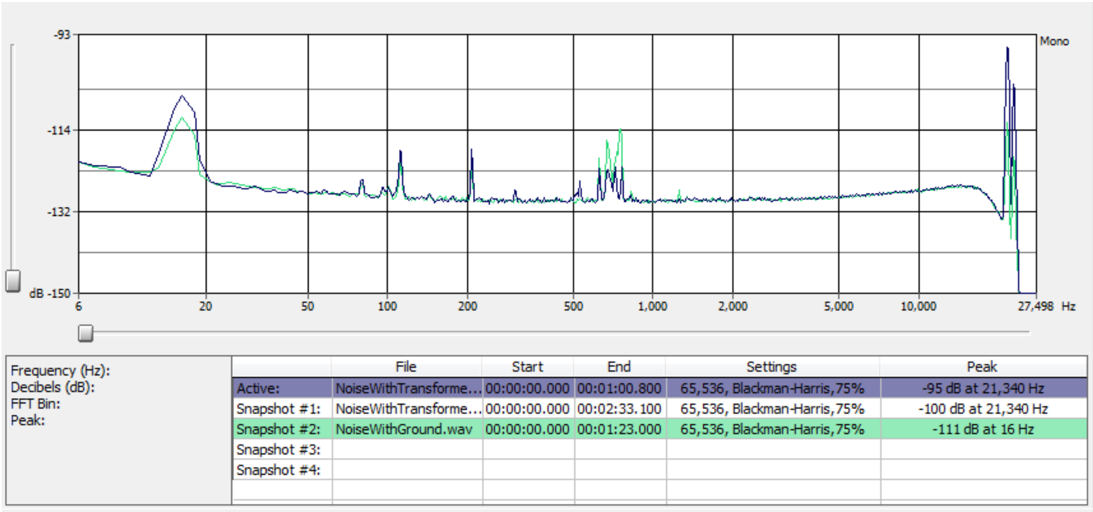


Figure 25: Spectrum with (blue) and without (green) transformer

After checking the impulse response of the tonearm by simply punching it, it turns out that a frequency resonance appears. The response is a strange because there is a first oscillation with a very short period, which is probably the vibration of the stylus. It seems that the following low frequency oscillation should come from the tonearm. The image bellow shows the complete impulse response with the two characteristic oscillations.

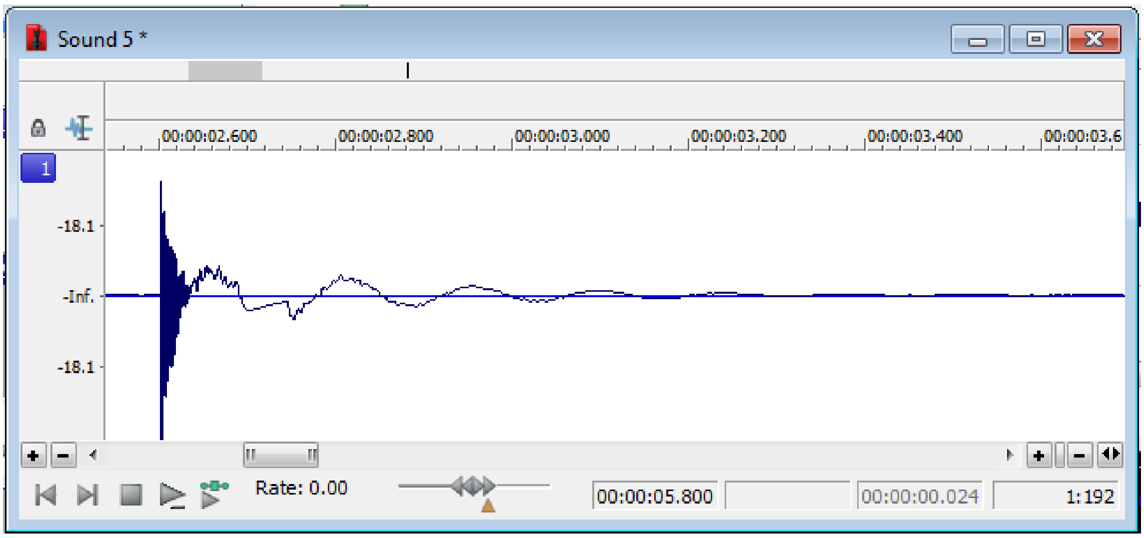


Figure 26: Impulse response of the tonearm

This image shows the first part of the impulse response with the high frequency oscillation. The stylus has a little mass but it is attach to the tonearm via a springy cantilever. The tonearm has a bigger mass than the stylus and the cantilever has a high spring constant. Therefore, a high resonance frequency is not so surprising. Than the stylus oscillation settle down and it is now the tonearm with its big inertia that swings.

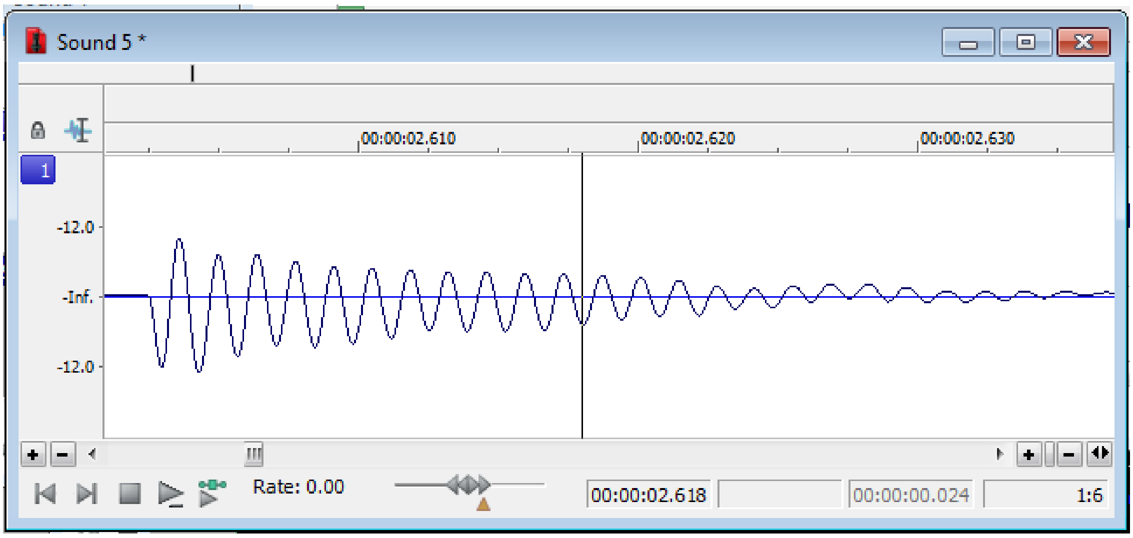


Figure 27: Zoom on the high frequency part of the impulse response

The stylus oscillation is clearly visible at around 640 Hz on the impulse response's spectrum. The tonearm resonate with a frequency around 10 Hz.

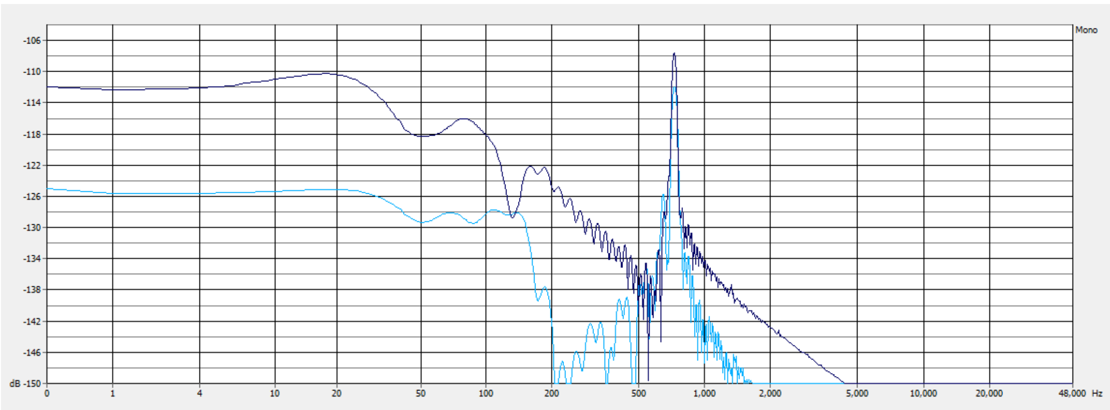


Figure 28: Spectrum of the high frequency part in sky blue and the complete impulse response

With the kind of high frequency oscillations, the mass and the energy in the system is so low that it can be easily disturb. In this case, a small experiment was performed with an elastic and a small mass (the clip) too see how the system reacts. In theory, this new element should attenuate the resonance.

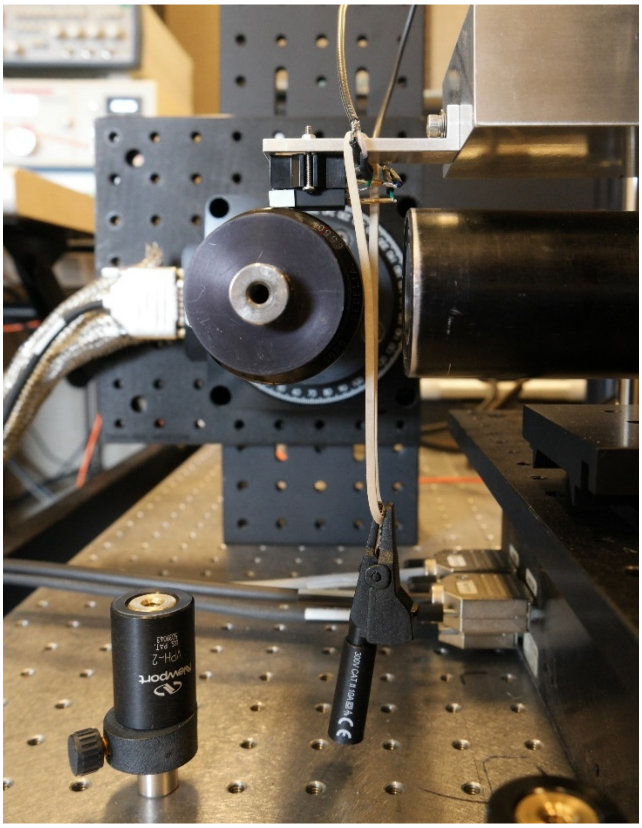


Figure 29: Elastic to attenuate the oscillation

The impulse response with this hack looks totally different and the high frequency oscillation has a smaller amplitude and is quickly attenuated. This trick is not directly applicable because the elastic would touch the cylinder but it was just to demonstrate that there is still some possible improvement. Either building a lighter tonearm or using some dampening techniques. The risk with dampening is the introduction of energy storage component that could easily complicate the system. Sometimes a simple light tonearm offer a better tradeoff between the efficiency of the system and the time spend to build and adjust it.

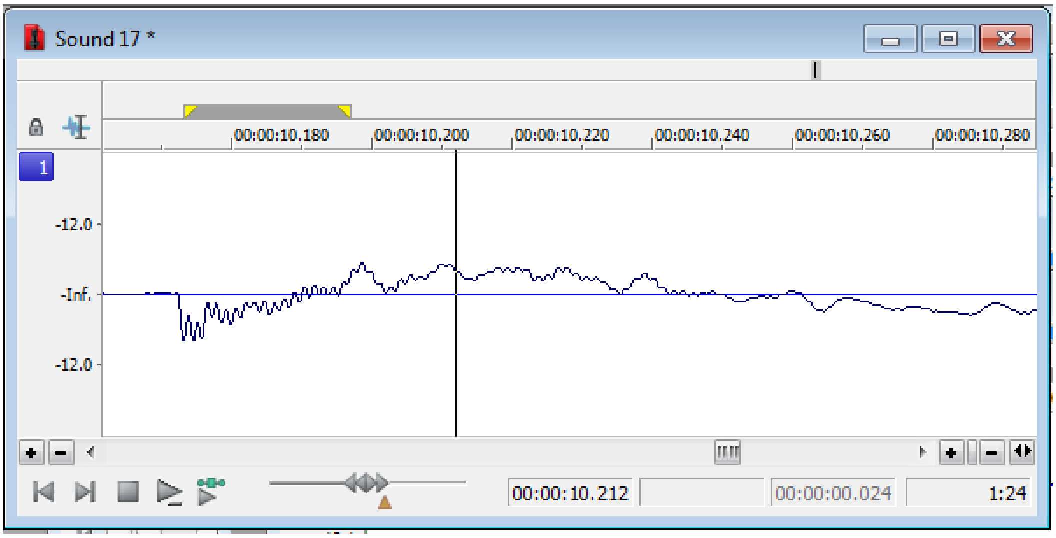


Figure 30: Impulse response with just an elastic

The attenuation is clearly visible in the following impulse response's spectrum. The dark blue is the tonearm with an elastic.

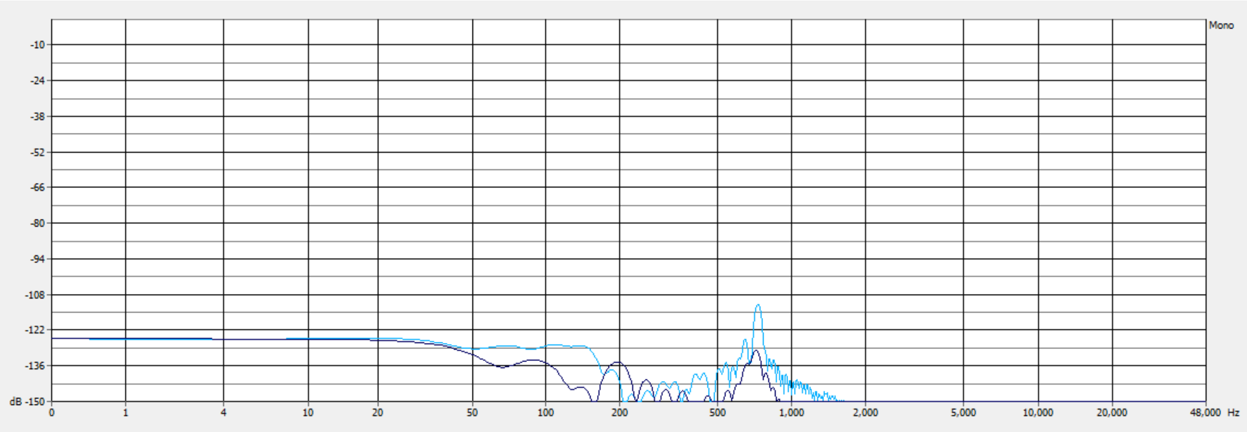


Figure 31: Spectrum of the impulse response with just an elastic

5 Image comparison

It is possible to evaluate the wearing of a cylinder using the audio spectrum but it would be better to directly analyze the surface. The resulting scan of a cylinder is in the form of a rectangular grayscale image with the pixel value being the surface elevation. This image-processing tool should be able to find the difference between images coming from different scans of the same cylinder. Because it is impossible to be sure that the cylinder is always on the same position, the software should be able to properly align both images. This method is called image registration.

5.1 Techniques overview

There is multiple ways to register two images but all methods do it in two steps. The first one is to find which part of the image is the same as the reference image. The second one is to transform the image to be the same as the reference one.

It is possible to do it with brute force computing by comparing the reference image with each part of the source image but it takes a lot of time with big images and it only works if the images are not too heavily warp or distorted. Feature detection is widely used in the computer vision field and there is now really efficient algorithm that realized this task.

5.2 SURF algorithm

One of the most used one is the SURF-algorithm (stands for Speeded Up Robust Features) invented in 2006 by scientists from the ETH Zurich and the Katholieke Universiteit Leuven in Belgium.

The SURF-algorithm uses three different steps to identify features: interest point, detection, local neighborhood description and matching. The first steps consists of finding all the key points that are probably in both images (the features) using square-shaped smoothing filters. Finally, a blob detector using local contrast change to select points that are the most distinctive. The second step consists of finding the orientation of the point so that if the image is rotated, both images are aligned in regards to that single key point. Finally, a ”descriptor” is created which describes how the neighborhood of each point looks like.

It is now possible to know how the image should be transformed to match the reference one.

5.3 Implementation

The big advantage of the SURF-algorithm is that it is already implemented in Emgu.CV (the C# version of Open CV), which is already used for the image processing with Prism. Another library called SimpleElastix was tried but after 6 hours of compilation, the example was not running. It is a shame because this library was developed for medical image processing and they spend a lot of time developing function to easily register brain images. However, there is not a lot of documentation and no information on the internet.

The function of the software could be resumed with the following drawing:

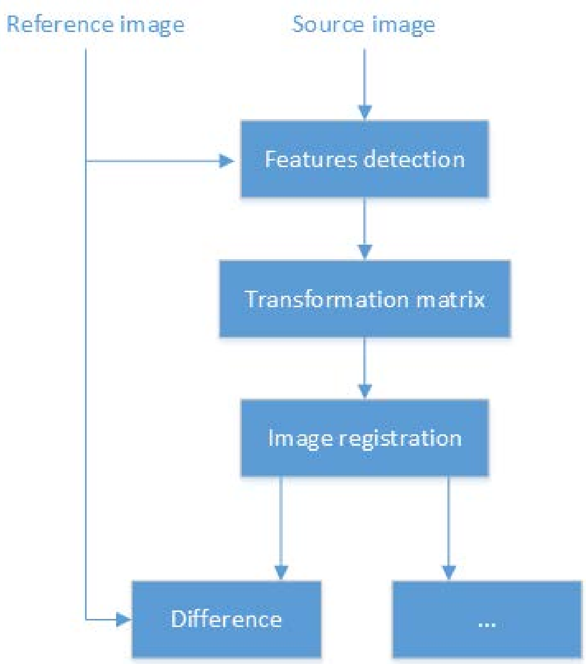


Figure 32: Function diagram of the image registration software

The software needs two input images. The first one is the reference images with the feature that we want to find in the source image. The program modify the source image to look like the reference image. At the end it is possible to compute any operation between the registered image and the reference one. In our case the difference between both images would be the most interesting one.

The feature detection using the SURF-algorithm is available as an example of the Emgu.CV Library

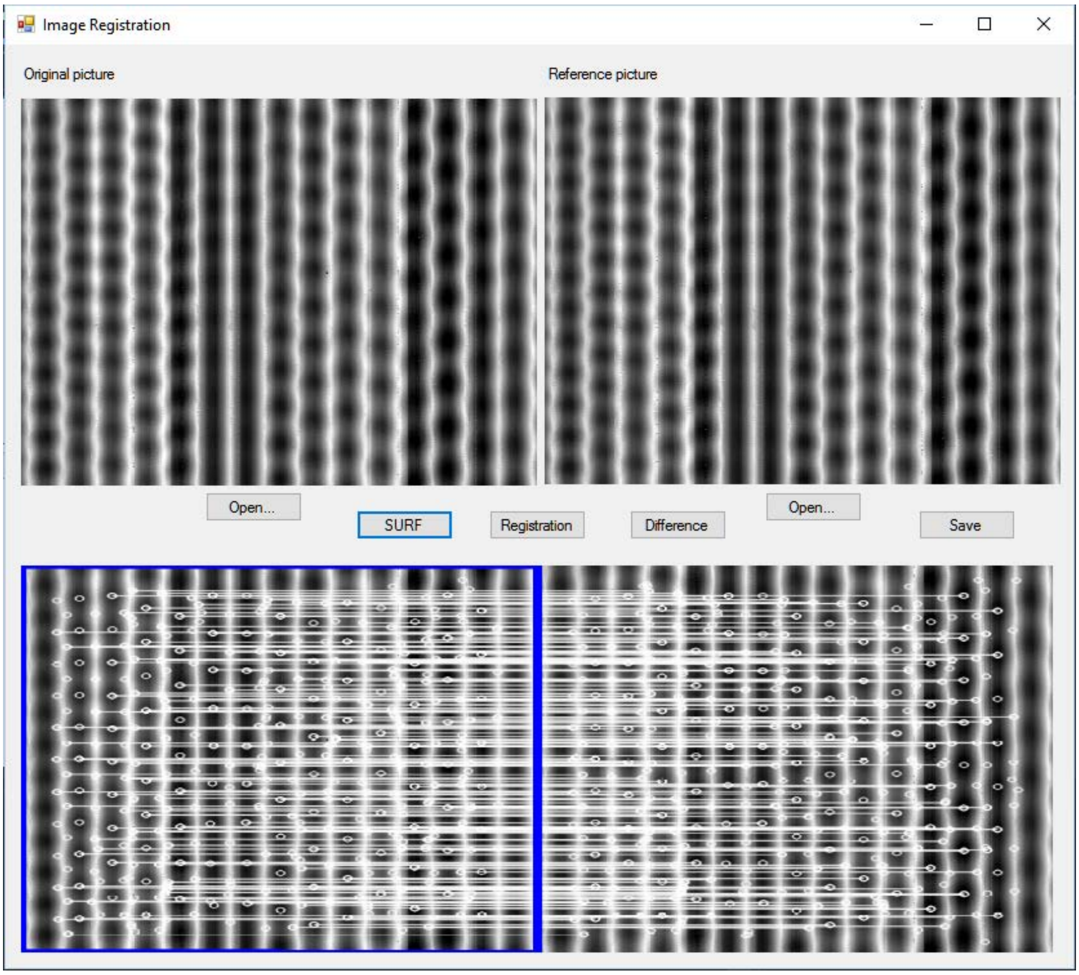


Figure 33: GUI of the image registration software

5.4 Baseline results

The first test to be sure that the algorithm works correctly is to compute the difference between two same images.

This test is to determine the baseline limitation of the software. Two scans of the same cylinder were performed one after the other. The two images from the same part were selected. After the registration of the images, the difference between both images was computed. The resulting image is dark which is a good sign! If everything was perfect the image should be a plain black rectangle but there is still a little bit of the structure visible. The height average of the surface was 0.3 µm which is a relatively small value compare to the height of the groove.

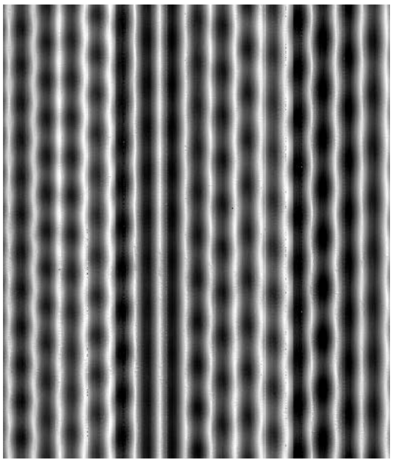


Figure 34: Source image

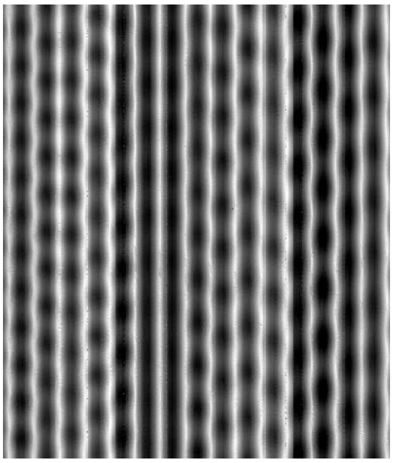


Figure 35: Reference image

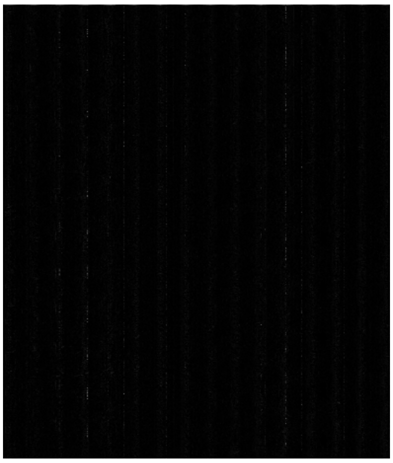


Figure 36: Difference between the source and the registered images

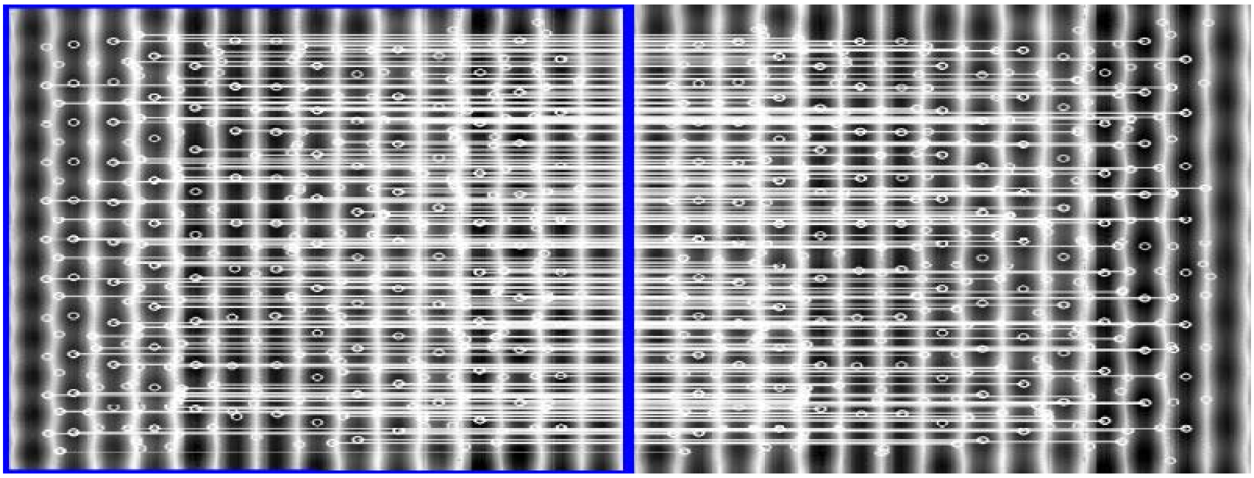


Figure 37: SURF-algorithm with the reference and the source file

The image on the bottom is the features detection using the SURF-algorithm. The two images are nearly identical. That is the reason why there is so much points and all the lines are nearly parallel.

This system works well when both images are similar. But when the software needs to register a complete cylinder it starts to be funny. It should be better to do many small registrations to find the best one instead of trying to do it with the whole cylinder.

6 Wearing methodology

6.1 Description of the methodology

6.1.1 Sound acquisition calibration

In order to have do proper playbacks with the phono cartridge the complete sound acquisition path needs to be calibrate. A commercial test cylinder was first played while adjusting the gain of the preamp without clipping. By knowing this reference level, it is possible to adjust both channels with a signal generator. At the minimal amplitude of the signal generator and with the internal 20 dB attenuator turned on, the signal was still too loud. A simple resistor divider was used as a complementary 20 dB attenuator (the exact value is not significant) in order to lower the signal within the range of the preamp. The difference between the maximum amplitude of the commercial records and this 1 kHz sinewave signal can be calculated. The gain of both channel was adjusted to reach a level of -12 dB to keep a little bit of headroom before clipping. The input signal of the preamp has very low amplitude so the signal was fluctuating between -12 dB with a ± 0.1 dB error.

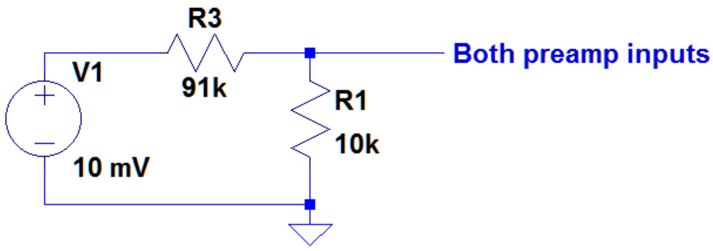


Figure 38: Circuit diagram to calibrate the preamp channel balance

Before doing any measurement, it is a good practice to caliber the pressure on the cylinder. This is best performed using a dedicated stylus scale. The surface of the scale should be placed approximately at the same height as the surface of the cylinder. The counterweight could be adjusted to reach the desired pressure. Stylus manufacturers generally advise a pressure between 2-3 g (20-30 mN). For this project a 2 g pressure was chosen. The following image shows the digital scale in action on a small platform used to adjust the height.

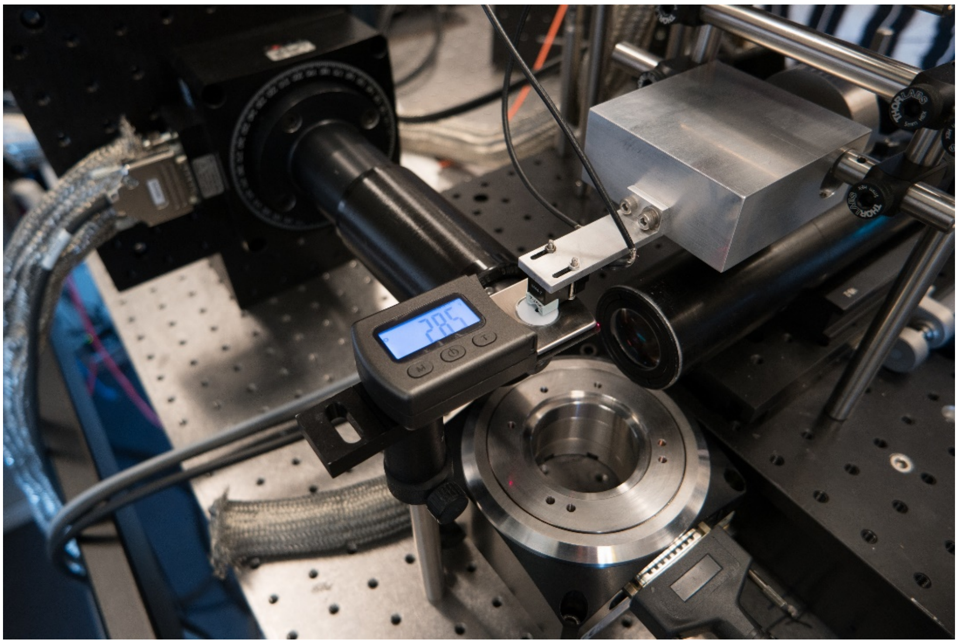


Figure 39: Stylus pressure calibration

The pressure has a big influence on the tracking of the groove. If the pressure is too low, the stylus could easily jumps from one groove to the other if the groove has a small defect. If the audio sounds “light”, it could mean that the pressure is too low. The scale used to calibrate the stylus pressure is an *Image Stylus Force Scale* with a 5 g capacity and a 0.01 g resolution.

6.1.2 Wearing process

The process is simple and consists off wearing one cylinder while keeping the other one as a “control” cylinder. An optical scan of the surface was performed before playing it. Then the cylinder was played 3 times and a new scan was performed. It is now possible to compare the state of the cylinder before and after the playbacks. It is also possible to compare the damaged cylinder with the control one.

6.2 Results

6.2.1 Noise level increase

The followings images come from the silence part of both cylinders. After computing the standard deviation of both signals, it turns out that the control cylinder has a RMS value of 0.21 µm where the damaged cylinder has 0.24 µm. So the noise level seems to increase with the wearing.

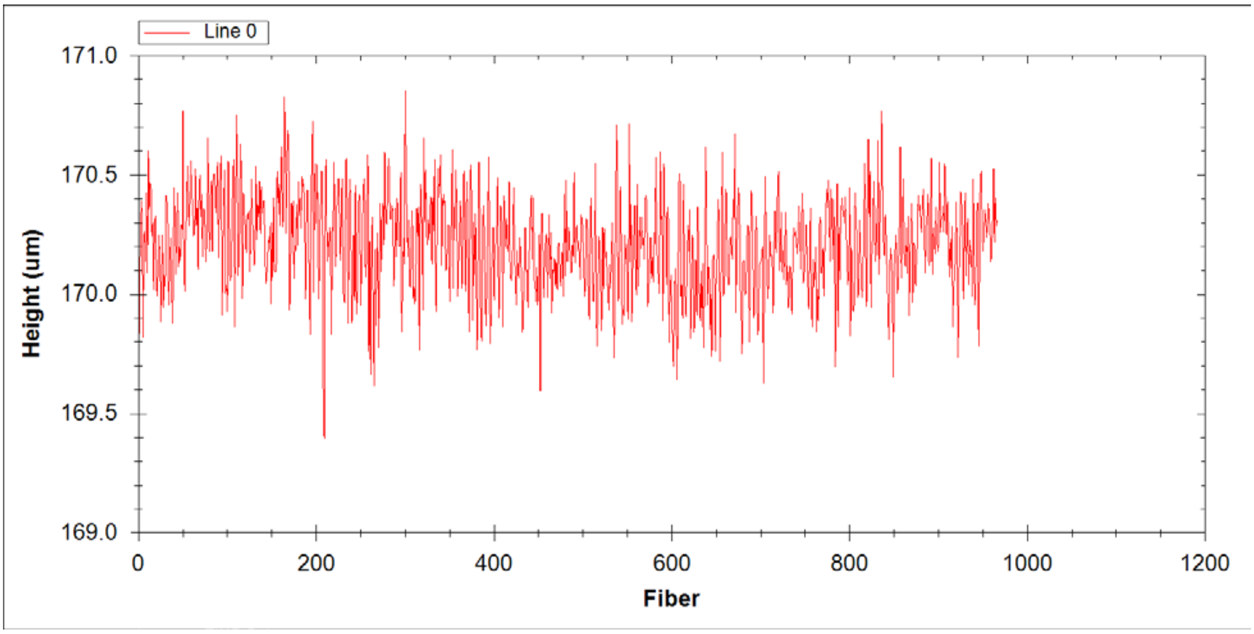


Figure 40: Noise of the control cylinder

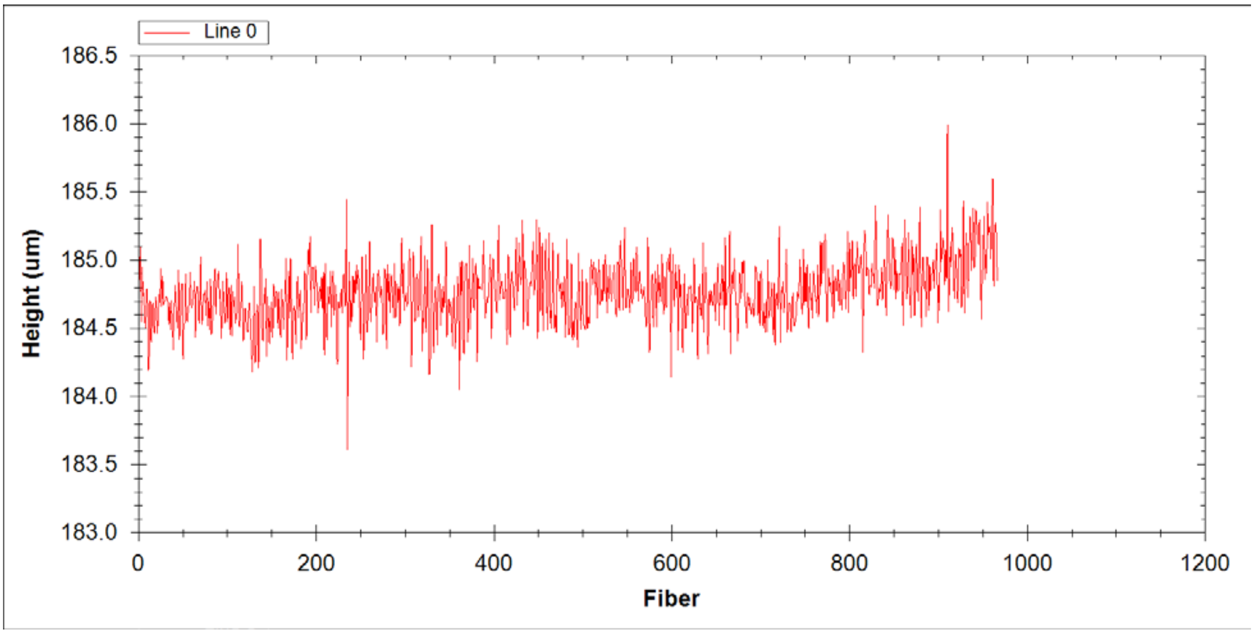


Figure 41: Noise of the played cylinder

6.2.2 Modification of the surface texture

After the cylinder was played 15 times, a difference in the surface texture becomes visible. The first image show the 1 kHz tone of the control cylinder. The second picture is the same 1 kHz but from the played cylinder.

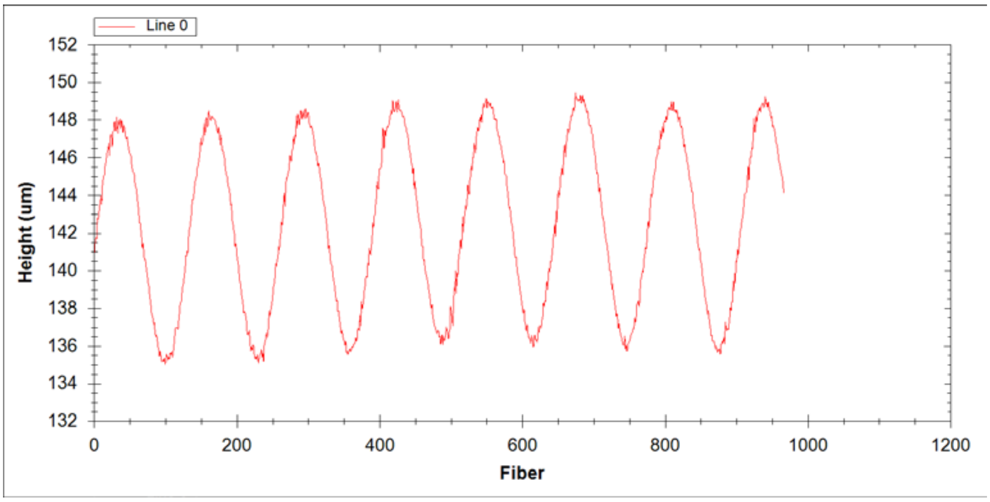


Figure 42: Surface texture of the control cylinder

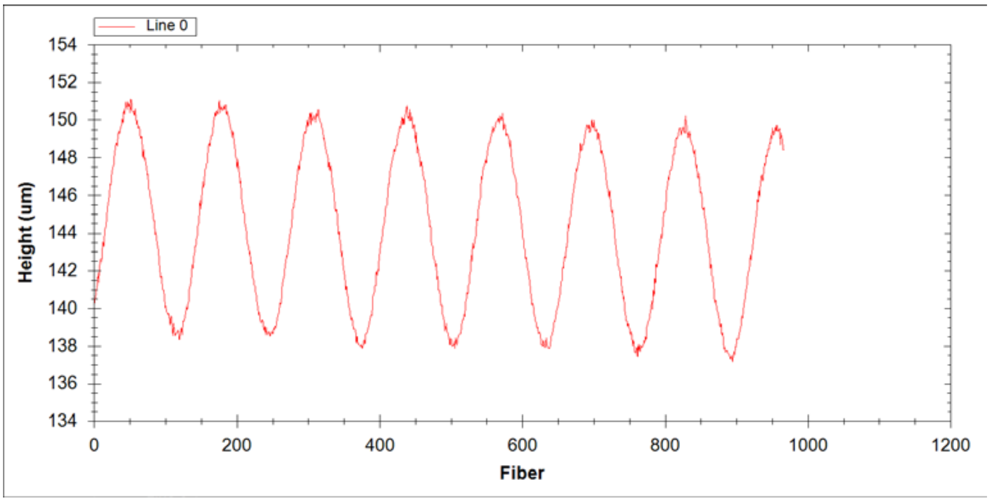


Figure 43: Surface texture of the played cylinder

The surface texture on the slopes is smoother on the played cylinder. This effect is well known in the vinyl records field. When a cylinder is cut, the cutting tool has also a resonance frequency and the cut itself is not perfectly. All these defaults produce a small roughness on the surface. By playing the record, the stylus will produce a higher pressure on this higher spots. Because the stylus as a constant vertical force, when the contact surface becomes smaller the pressure increases. If this pressure is high, enough the wax would be deformed until the surface become smooth. This side effect is called burnishing and this technique is widely use to polish malleable (often precious too) metals like gold and silver.

7 Conclusion

7.1 Summary and discussion of the work performed

During this project, a mechanical phonograph was built in order to perform some wearing tests on cylinders. The first attempt to build a passive phonograph was a complete failure. Given the fact that the second one was a hack with the pieces of the first one it performs good. Couples of mechanical artifact showed up in the audio reproduction but they could probably be solved by building a better tonearm more suited for this task. The bulky tonearm was design to house linear bearings, which are not used any more. Changing this bulky piece of aluminum with a lighter tonearm could improve the audio quality. The distortion of the phonograph is around 1%, which is decent for this kind of device.

7.2 Further work

This project served as a starting point to really understand the complex interaction between the stylus and the record's surface. There is a lot more to do! A good improvement would be to redesign the tonearm. It is actually too heavy. There is also a lot to do about the measuring techniques. In fact, most of the value measured are really near the noise level. Some measures are not always reproducible. The same measure could deliver different results, which tend to compromise the analysis.

The image registration software could also be greatly improve. It sometime works with small samples but it simply does not work with a complete cylinder for example.

7.3 Personal conclusion

This project give me a first contact with audio preservation techniques and I really enjoyed it. Playing my first cylinder with the phonograph and being able to hear it was a huge satisfaction. It is also interesting to listen to historical records and reproduce the quality they had back in the early twentieth century.

This project also gave me the opportunity to learn new CAD tools and design this small contraption. I believe that multidisciplinarity is a great value for every engineer. This project started with some mechanical conception, some image processing, and a lot of data analysis. It was a complete project. This kind of research project are always interesting because you can never exactly predict what you are going to find which is not easy to plan. Some tasks were supposed to last less than other did and there was some surprise. For example fighting electrical noise is really an art! Working with oscillations and vibrations in the micron range tend to make the work harder. This project was very fruitful in knowledges.

8 List of Figures

9 Glossary

HEIA-FR: *Haute-école d'ingénierie et d'architecture de Fribourg*, School of Engineering and Architecture of Fribourg

FFT: Fast Fourier Transform

SURF: Speeded Up Robust Feature

IRENE: Image, Reconstruct, Erase Noise, Etc.

Keyence: Manufacturer of the laser used to measure the distance from the camera to the disc in order to perform autofocus. Name used by the IRENE team.

LBNL: Lawrence Berkeley National Laboratory

VI: Virtual Instrument

Virtual Instrument: a LabView file, usually a program that can be run and often controls physical instruments

10 References

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[6] M. J. Di Toro, *Distortion in the Reproduction of Hill-and-Dale Recording*, (1937)

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[8] G. Vogel, *Is a Failing Bearing Causing the Vibration?* , [online] available: http://ecmweb.com/motors/failing-bearing-causing-vibration, (2013)

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[10] *Conversion Factor, Ratio, or Gain to a Level Value (Gain Decibels dB) and vice versa,* [online] available: http://www.sengpielaudio.com/calculator-FactorRatioLevelDecibel.htm

[11] POPPY Records, *Electrically-Recorded Calibration Cylinders*, [online] available: http://www.poppyrecords.co.uk/CXP003/cxp003.htm

[12] http://www.cairn.info/revue-societes-et-representations-2016-1-page-149.htm#pa22

11 Appendices

11.1 Audio files descriptions

Definitions:

- LR: Low-resolution optical scan (64 kHz sampling frequency)
- HR: High-resolution optical scan 128 kHz sampling frequency)
- S: Slow (rotation speed < 160 rpm)
- F: Introduction of the Focusrite Scarlett 2i2 USB audio interface

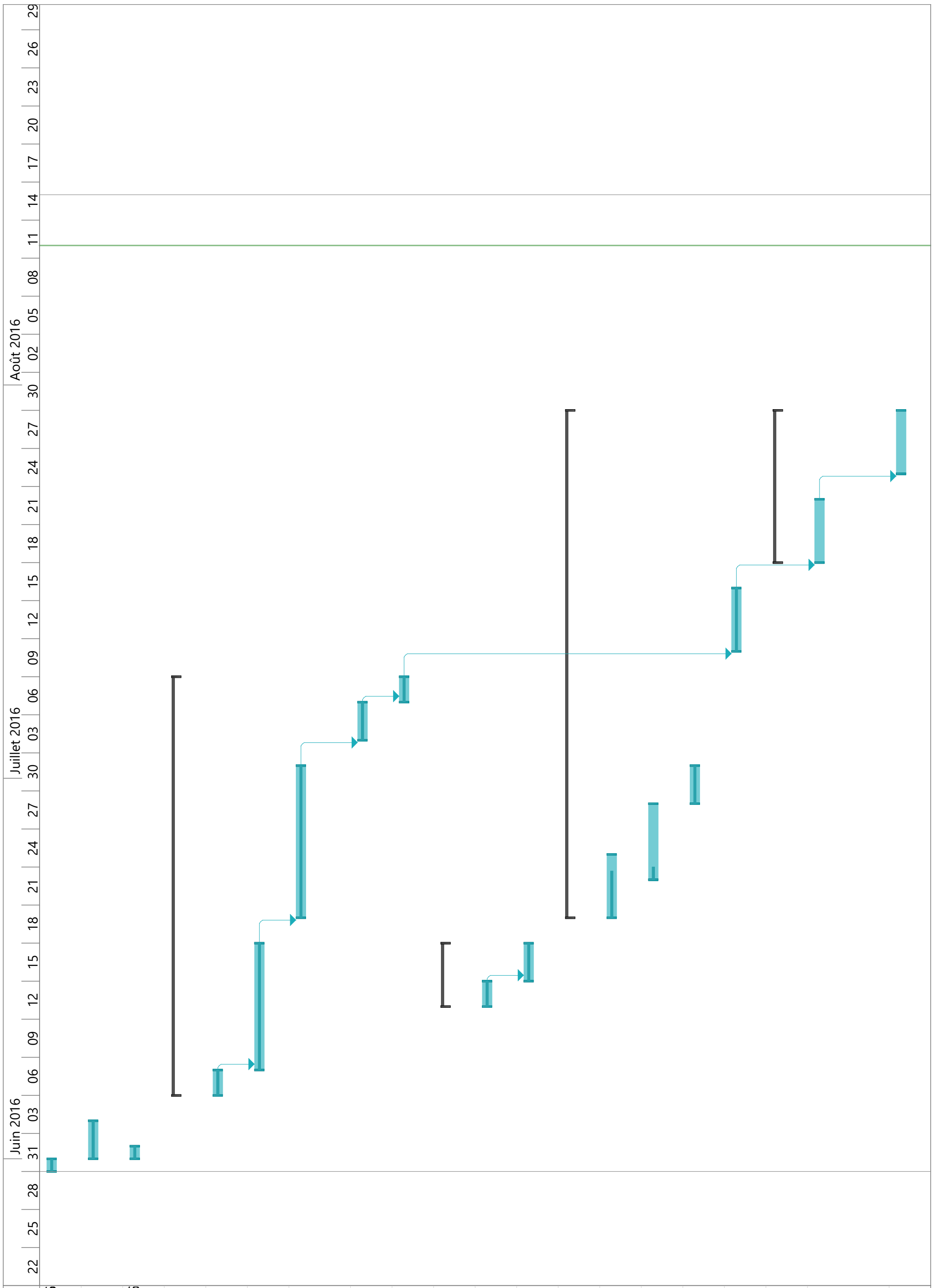
Folder name	Note	CXP003A Playback	CXP003A Scan	CXP003B Playback	CXP003B Scan	Description
01_WorkingInTheMovies_Stylus	S					First test with the cartridge -> proof of concept (200 TPI)
02_Bedella_Stylus	S					Same but for a 100 TPI cylinder
03_CXP003A_BeforeWearing_Optical			LR			Optical scan of the played cylinder to have a reference
04_CXP003A_FirstWearing_Stylus	S	1				First stylus playback of the test cylinder
05_CXP003A_FirstWearing_Optical_WrongParameters			X			Optical scan to see if something happened! Wrong parameters, scan unusable
06_CXP003A_FirstWearing_Optical_Right			LR			Optical scan but with the right parameters this time
07_Bedella_CW_vs_CCW	S					Test to see the influence of the rotation direction (because we're turning in the wrong direction)
08_CXP003A_SecondPlaybackStylus	S	2				Second playback with the stylus
09_CXP003A_FourthOpticalScan			LR			Optical scan to see if something changed
09_CXP003A_ThirdOpticalScan_Noisy			X			Optical scan but weird noise (problem with parameter…)
10_NoiseCorrection	S					Various tests with the stylus not touching the cylinder to find the origin of the noise
11_CXP003A_ThirdPlaybackStylus	S	3				Playback with the stylus but still with a rotation speed under 160 rpm
12_CXP003A_HighResolutionScan			HR			Changing the resolution of the scan to have more headroom in the frequency response
13_FourthPlaybackStylus	S	4				Stylus playback
14_FifthPlaybackStylus160rpm		5				Override of the rotation speed limitation. Now 160 rpm is possible
15_PlaybackDifferentPhase						Test by rotating the cylinder to introduce a phase between the two playback to test if the noise come from the rotary stage
16_NewPlaybackDifferentPhase						Second test
17_PlaybackSecondStage						Testing a different stage to see if the noise change with the stage
18_NoisePickupAround1Khz						Testing the noise around 1 kHz

19_Noise						Fighting noise!
20_SixthPlaybackStylus		6				Better quality playback with the higher speed and some tweaks.
20b_StylusPlayback		7				Same as the previous one but by improving the mechanic
21_BedellaSecondPlayback						Testing with a commercial cylinder
23_CXP003AOpticalScan			HR			High resolution scan of the played cylinder
24_CXP003BOpticalScan					HR	High resolution scan of the control cylinder
25_LR						Doing some tests to control both left and right channels
26_CXP003BTest1kHz					HR	Doing some scans of the 1 kHz sinewave to test the image registration software
27_CXP003BTest2					HR	Same as the previous one but to get different samples
28_2Scans			HR		HR	Scanning two times the same part to get the baseline of the image registration software
29_CXP003ACompleteScan			HR			Complete optical scan of the played cylinder
30_NinethPlayback		8				New improved playback
31_BedellaPlayback	F					Test with a commercial cylinder, some tracking problems
32_BedellaOpticalScan						Optical scan of the commercial cylinder to compare with the stylus playback
33_WearingTest		19				Doing multiple playbacks to see if it introduce some noise or other effects
34_WearingTestScan			HR			Optical scan of the test cylinder
35_WearingTestScanAfter			HR			Optical scan after the wearing test
36_CXP003BHighResScan					HR	High resolution scan of the control cylinder
36b_CXP003BFirstWearing				1		Playing one time the control cylinder to observe the burnishing
37_CXP003BSecondScan					HR	Second optical scan to analyze the effect
38_CXP003BSecondHighResScan					HR	Complete scan of the control cylinder
39_ImpulseResponse						Impulse response of the tonearm+cartridge

The most interesting files are after the introduction of the Focusrite audio interface.

11.2 Planning

N°	Mode Tâche	Nom de la tâche	Durée	Début
2		Project introduction	1 jour	Mar 31.05.16
3		Reading documentation	3 jours	Mer 01.06.16
4		Sacnning test records	1 jour	Mer 01.06.16
5		**Designing a wearing machine**	**25 jours**	**Lun 06.06.16**
6		Learning Solidwork	2 jours	Lun 06.06.16
7		Designing wearing contraption	8 jours	Mer 08.06.16
8		Waiting on the machine shop for pieces	10 jours	Lun 20.06.16
9		Wearing test cylinders	3 jours	Lun 04.07.16
10		Scanning test cylinders	2 jours	Jeu 07.07.16
11		**Image correction toolbox**	**5 jours**	**Lun 13.06.16**
12		Image registration	2 jours	Lun 13.06.16
13		image warping correction	3 jours	Mer 15.06.16
14		**Deveolopping a test methodology**	**30 jours**	**Lun 20.06.16**
15		Image comparaison	5 jours	Lun 20.06.16
16		Surface rugosimetry	4 jours	Jeu 23.06.16
17		Audio spectrum comparaison	3 jours	Mer 29.06.16
18		Quantify wearing	5 jours	Lun 11.07.16
19		**Correction algorithm**	**10 jours**	**Lun 18.07.16**
20		Developping wearing correction algorithm	5 jours	Lun 18.07.16
21		Testing algorithm on test cylinder	5 jours	Lun 25.07.16



N°	Mod Tâch	Nom de la tâche	Durée	Début
22		**Documentation**	**50 jours**	**Lun 06.06.16**
23		Introduction	10 jours	Lun 06.06.16
24		Theory	5 jours	Lun 13.06.16
25		Wearing machine	5 jours	Lun 20.06.16
26		Image correction	10 jours	Lun 27.06.16
27		Test methodology	5 jours	Lun 11.07.16
28		Wearing correction algorithm	5 jours	Lun 18.07.16
29		Results	10 jours	Lun 25.07.16
30		Finishing documentation	5 jours	Lun 08.08.16
31		Report publication	0 jour	Lun 15.08.16