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Sound & Visual Technology

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Utilization Possibilities of Piezoelectric Pickups in Recording Arts

Master’s Project

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Viljandi 2024

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Abstract:

Piezoelectric pickups, known for their widespread use in acoustic guitars and various instruments, might hold untapped potential beyond these established applications. This research aims to investigate this potential through a qualitative exploration centered around studio recordings. This project aims to investigate the utilization possibilities of piezoelectric pickups in recording arts. The research includes a comprehensive review of the existing literature on piezoelectric pickups and their applications in recording arts, as well as original experiments and analyses of the sound quality and characteristics of piezoelectric pickups in different recording scenarios. The research presented in this project is intended to contribute to the ongoing development of recording arts and provide new insights into the potential uses of piezoelectric pickups. It is my hope that this work will inspire further research and experimentation in this field.

Keywords:

Contact microphones, piezoelectricity, transducers, recording arts

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Introduction

The world of music recording relies heavily on a diverse arsenal of microphones, each offering unique sonic characteristics. Piezoelectric pickups, affordable and familiar components frequently found in acoustic guitars, and various string instruments represent a well-established yet potentially under-explored technology within this vast array. While their functionality is well-defined, their applicability in broader recording scenarios remains a largely uncharted territory.

This Master's project delves into the potential of piezo pickups beyond their traditional applications. Through a qualitative exploration centered around studio recordings, the project aims to unlock new sonic possibilities for these versatile transducers. To achieve this, the research will encompass several key aspects:

- A comprehensive review of existing literature on piezoelectricity and its current applications in the recording arts.
- Original experiments that analyze the sound quality and behavior of piezo pickups in various recording situations.
- An examination of how piezo pickups can be utilized with several instruments not typically associated with them.
- Exploration of creative uses for piezo pickups that extend beyond traditional microphone roles.

This research seeks to contribute to the advancement of recording practices by exploring these aforementioned avenues. It endeavors to illuminate the unrealized potential of piezo pickups and stimulate further research within this domain, ultimately expanding the spectrum of sonic possibilities accessible to recording professionals.

1 Theory

1.1 Transducers

Transducers serve as fundamental elements in the realm of energy conversion. They possess the capability to transform various forms of energy including temperature, motion, light, pressure, torque, and position, into electrical signals. This conversion facilitates unimpeded measurement and utilization of these energies. Two distinct categories characterize transducers: active and passive. Active transducers function in an autonomous manner, directly converting energy into an electrical signal without requiring any external power source. A classic example is a thermocouple, which translates temperature differentials into voltage. Conversely, passive transducers necessitate an external energy source to operate. Their functionality hinges upon detecting alterations in intrinsic electrical properties such as capacitance, resistance, or inductance. The significance of transducers lies in their ubiquitous presence within a multitude of applications. (Agrawal, 2017, s. 65)

In the world of sound, as a device that converts energy from one form to another, the transducer is a crucial element. Microphones are a common example of a transducer. Here, sound waves in the air move the microphone's diaphragm, converting this motion into electrical current fluctuations that travel through wires to amplifiers or recording equipment. Loudspeakers demonstrate the reverse transduction process. Electrical current variations carried by wires are converted into changes in the speaker magnet's magnetic field. This, in turn, moves the speaker's diaphragm, creating air pressure fluctuations or sound. (Gotfrit, 1999)

1.2 Introduction to Piezoelectricity

Piezoelectric materials hold a niche within the realm of mechanical input transducers. These materials offer the unique ability to convert mechanical stress into a measurable electrical signal. This functionality makes them valuable tools for applications requiring the measurement of pressure, force, displacement, and various related physical phenomena. The underlying principle behind piezoelectricity involves the response of the material's internal crystal structure to mechanical strain. When a piezoelectric material is stressed in a specific direction, a unidirectional separation of its resident electric charges occurs. This separation results in the formation of an effective net charge on a capacitor created by metallic electrodes bonded to the material's surface. Essentially, the mechanical strain acts as a trigger, inducing a measurable electromotive force (EMF) across the material. Piezoelectric materials encompass both naturally occurring crystals and synthetically produced ceramics. Common examples of natural piezoelectric materials include quartz, Rochelle Salt, and ammonium dihydrogen phosphate (ADP). Conversely, barium titanate, lead zirconate-titanate, and lead-meta niobate represent examples of synthetically derived piezoceramics. It’s worth noting that all piezoelectric materials possess a defining characteristic known as the Curie temperature. This temperature threshold marks the point above which the material loses its piezoelectric properties. (Northrop, 2005, s. 241)

The piezoelectric effect was first observed in the 1880s in naturally occurring materials. However, it was during World War II that man-made polycrystalline ceramic materials with piezoelectric properties were developed. These materials expanded the range of piezoelectric applications to include sonar, hydrophones, and piezo-ignition systems, in addition to microphones, accelerometers, and ultrasonic transducers that had already been developed using natural crystals. (Ebrahimi, 2013, s. VII)

Piezoelectric pickups can be classified under passive transducers, as they “convert acoustical energy directly into electrical energy (and vice-versa) without the need for any external power feed.” (Boré & Peus, 1999, s. 9)

1.3 Working Principals of “Conventional Microphones”

Throughout this work, conventional microphones will refer to the common types of microphones that, through their respective working dynamics, capture the sound that “propagates … as a longitudinal wave.” (Nave, 2001) and the speed of which “is determined by the properties of the air, and not by the frequency or amplitude of the sound.” (Nave, 2001) However, while piezoelectric pickups are mostly insusceptible to sound waves traveling in the air, most conventional microphones, mainly in connection to the pressure gradient principle, are susceptible to handling noise or vibrations directly transmitted to the microphone itself. As for how these microphones all work and how their working principals differ from or share similarities to those of piezoelectric pickups, the following brief information could be helpful:

Dynamic microphones work by converting sound waves into electrical signals using a moving coil and magnet. However, the design requires a strong sound source to generate a signal because the coil itself has some weight. This makes them less sensitive to quiet noises compared to other microphone types. Despite this, dynamic microphones are a good choice when capturing loud sounds or when high sensitivity isn't crucial. They are also very durable due to their simple construction and can handle moisture and loud noises without being damaged. (Huang & Shiu, 2015, s. 2)

Condenser microphone‘s function is based on a tiny distance change between two thin plates. These plates act like a particular electrical component called a capacitor. One plate is fixed in place, while the other is very thin and flexible, able to move slightly. Sound waves cause the thin plate to vibrate, which changes the distance between the plates. This change in the distance directly affects the capacitor's ability to store electrical charge. By monitoring these changes in capacitance, condenser microphones convert sound waves into electrical signals. (Frederiksen, 2008, s. 1247)

The ribbon microphone is made from a thin metallic ribbon that can vibrate in response to air vibrations coming from either side while hung in a magnetic field. An electromagnetic field (emf) equivalent to the incident sound wave's undulations is created when an impressed sound wave causes the ribbon to vibrate. The pressure differential between the two sides causes the ribbon to shift from its equilibrium position (making it a pure pressure-gradient microphone). The ribbon is manufactured light such that, at very high frequencies, its velocity matches that of the air particles. This sort of microphone has distinct directional qualities, which is one of its main advantages over a pressure-operated microphone. (Olson, 1931, s. 695)

2 Methodology & Analysis of the Collected Material

In this Master's Project, I have adopted a qualitative research approach, exploring under-utilized applications and artistic potential of piezoelectric pickups. The core data stems from a series of multi track studio recordings where I experimented with various non-traditional uses of the technology. The specifics of these sessions, including instruments and recording setups, will be under each chapter. During these sessions, the aim was to capture a diverse range of sounds and textures achievable with piezo pickups.

These recordings were analyzed using iZotope RX, an audio restoration tool with a wide array of audio restoration and analysis capabilities. Here, I frequently utilized spectral imaging tool, which according to iZotope is: "a detailed, three-dimensional audio visualization tool" (iZotope, 2024) and which displays "a range of frequencies, with the lowest frequencies positioned at the bottom and the highest at the top." (iZotope, 2024), which also " depicts the loudness of events across these various frequencies." (iZotope, 2024). This allowed me to examine the resulting sonic characteristics further. Additionally, iZotope RX was employed for loudness normalization, ensuring the recordings adhered to EBU-R128 standards for consistent playback levels. Through this combined approach of spectral analysis and in-depth audio analysis, I identified unique sonic qualities and patterns associated with these non-traditional piezo applications. These findings became the foundation for exploring the artistic possibilities this technology holds.

While my exploration through recordings forms the core research, the findings are contextualized and supported by existing research on piezoelectric pickups. This involves referencing relevant scientific articles and respected journals to achieve two goals: firstly, to establish a baseline understanding of the technology and its established applications, and secondly, to identify potential connections between my research findings and existing theoretical frameworks related to sound production and manipulation. Drawing on original recordings and established knowledge, this interwoven approach strengthens the overall research narrative. Obstacles encountered during the research process and the solutions I implemented will be addressed in a separate chapter titled "Challenges-faced and Recommendations"

Through this process, I have conducted various tests to draw solid conclusions. I have used examples of real-life recordings as well as tests designed solely for conclusion-drawing purposes. With the real-life recording scenarios, I have decided on the choice of microphone and its placement only in accordance with the artistic aim, whereas with the tests; I have made the utmost effort to use as many variations of piezoelectric pickups and conventional microphones as possible, specifically implementing whenever possible, the use of omni directional microphones along with microphones of other characteristic traits (mainly cardioid microphones). In most instances, I have then exported and attached both the dry and “wet” (or mixed) versions of the audio files (or songs) along with their accompanying spectrogram image for visualization purposes.

To have more comparable audio and visual examples, I used the Loudness Control plug-in of iZotope RX 10 to normalize all the audio clips presented during this work. I have chosen the EBU R 128 standard (European Broadcasting Union, 2023) as a normalization preference for the whole project since it respects the dynamic range of the audio files whilst keeping the audio at a reasonably high level for playback. I've included two versions of the recordings: mixed versions (some happened to be the finalized versions) that combine the piezo and conventional microphone audio and the original, separated recordings. This lets you hear how the sounds captured by the piezo pickup, which works differently than a conventional microphone, can be blended with the microphone audio to add certain qualities or to create unique effects that mixing engineers and listeners might appreciate.

3 Testing Potential Real-Life Applications for Piezo Pickups

3.1 Comparison of Different Sizes of Piezoelectric Pickups

In order to draw a conclusion concerning the sensitivity towards amplitude and frequency response, I have recorded and analyzed the sound of a floor tom with piezoelectric pickups taped to the bottom skin. For this test, I have used 15, 18, 20, 27, 35, and 50 mm piezoelectric pickups. All of them were recorded simultaneously, using the same preamps, and all were recorded at unison gain. **Table 1**. *Loudness comparison of various sizes of piezoelectric pickups***Table 1** can be used to better visualize the gain sensitivity of various sizes of piezoelectric pickups, utilizing the data acquired during the test that I have conducted. The main purpose of the table and its contents is to demonstrate how, at unison gain from the pre-amps, these components of differing sizes compare to each other in terms of their sensitivity to amplitude in loudness units full scale (LUFS).

Table 1. *Loudness comparison of various sizes of piezoelectric pickups*

Piezo Size (mm)	**Loudness (LUFS)**
15	-44.1
18	-35.2
20	-36.6
27	-33.5
35	-28
50	-23.8

The first thing that could be mentioned is how quiet these components can be and their need to be amplified, which, while recording, is not something that can be overlooked. So, using as big of a piezo as possible, considering the size and the limitations of the instrument, helps drastically with the need to add additional gain. It can also be surmised that through this test, it’s possible to see the proportional augmentations in loudness with the increased diameter of the piezoelectric pickups.

As for the frequency responses, we can look at the spectrogram images featuring not only the piezoelectric pickups attached to the bottom of the drum but also an omnidirectional condenser microphone as a reference. The omnidirectional microphone was positioned approximately 20 cm from the top skin of the drum and was gain-matched to EBU R-128, along with the audio from piezo pickups, to show a comparable frequency response. (see **Table A1 I,** *Audiovisual Material Mentioned in 3.1* :, FT_SOmni_1_p, FT_50mm_1_p, FT_35mm_1_p, FT_27mm_1_p, FT_20mm_1_p, FT_18mm_1_p, FT_15mm_1_p) The reason I choose to use these examples is that Floor Tom presents sustained notes and a wide frequency spectrum. My deductions from these visuals are, first and foremost, the sensitivity to bass frequencies and how they increase with the diameter of the piezo pickups. One other deduction I’ve made from these visuals has been the augmentation of the frequency response between 2000 to 4000 Hz, visibly augmenting parallel to the diameter from 15mm until 27mm and then showing a decline. Another reasonable deduction we can draw from these tests is when compared to an omnidirectional condenser microphone, we can see the bass frequency response is only truly replicated with the 50mm piezoelectric pickup. And whilst the 35mm piezo shows some of the bass frequencies, piezo pickups smaller in diameter have much less visible bass information.

From this test, we can deduce that the diameter of the piezoelectric pickup not only affects the sensitivity and overall output gain but also has an impact on the sensitivity towards bass frequencies.

3.2 Oud

The following material was recorded during the recording sessions for my album “Thank You For Your Time” (UPC: 198026865465). The tracks are taken from the track “Bazen” (ISRC: USY282322609) and feature a partition of the Turkish classical instrument Oud, which was composed, performed, and recorded by me.

In this recording, oud was recorded using a Shure SM57, running through a Triton Fethead Preamplifier, and a 50mm piezo pickup, mounted under the soundboard, right below the instrument's bridge, using fast-drying epoxy. Piezo is recorded directly into an audio interface without any additional processing/amplification.

These tracks are featured both in the song context (see **Table A1 II,** *Audiovisual Material Mentioned in 3.2* OM_BazenCoda_w) and as separate, isolated recordings (see: **Table A1 II,** *Audiovisual Material Mentioned in 3.2* OR_Piezzo_w & OR_SM57_w).

When compared visually, (see **Table A1 II,** *Audiovisual Material Mentioned in 3.2*: OR_Piezzo_p & OR_SM57_p), the fundamental visible difference between the isolated recordings is the amount of emphasis on the bass frequencies on the piezo recording and the lack of ambient noise compared to the SM57. As for sonic characteristics, the piezo pickup has a direct and very dry sound, which is similar to that one might expect to hear in a DI acoustic guitar recording.

One other comparison that can be made is on the prominence of the fretting noise captured by the SM57 and the complete lack of it in the piezo recording.

Using these recording methods together provides the advantage of having the attack and sibilance of piezo pickup combined with the SM57's presence, or "room tone" (Holman & Baum, 2005, s. 162). Having a more prominent mid-range, (particularly between 1kHz and 5kHz) and capturing the attack and the essence of the sound without compromising the fretting and vibrato sounds that come from the fretboard.

3.3 Hiiu Kannel

To showcase not only another potential use cases of piezoelectric pickups, but also the effects of their placement on the instruments' bodies, I have conducted a recording of the Estonian folk instrument Hiiu Kannel. The recordings took place on the March 2nd, 2024, and they feature the Nordic folk tune Stenåldersvalsen, performed by Greta Liisa Grünberg. The recordings consisted of 4 tracks (see **Table A1 III,** *Audiovisual Material Mentioned in 3.3*: HK_9559_h & HK_9560_h) 2 piezoelectric pickups and two microphones (one Schoeps small diaphragm cardioid and one Schoeps small diaphragm omni microphone). The reasoning behind the piezoelectric microphone placements in these locations was an examination of the instrument and a determination of potential places to apply these pickups temporarily and externally, as well as a field test of trying to determine where the instrument vibrated the most. In order to create a deeper recording with all the characteristics of the instrument present, I employed conventional microphone recordings in the mix as well.

When analyzed, we can see in the dry recordings how the sensitivity differs between not only conventional microphones and piezoelectric pickups but also based on the piezo pickups' locations. We can deduce from the spectrogram images that when distanced further from the sound hole, piezoelectric pickups are less susceptible to high frequencies and, in an inverse proportion, susceptible to low frequencies. (see **Table A1 III,** *Audiovisual Material Mentioned in 3.3* : Piezo N1 signifying the one closer to the sound hole and Piezo N2 signifying the one by the bridge HK_RecPiezoN1_1_p & HK_RecPiezoN2_1_p).

When we take a listen at the final mix (see **Table A1 III,** *Audiovisual Material Mentioned in 3.3*: HK_RecordingMixed_w), we can hear that the full representation of the instrument timber, the low end from the piezo pickups, the added presence & bowing sounds from the conventional microphones, as well as the effects added per players preferences, create a full image of the instrument. This effect can be further explored with the separately exported piezo and conventional microphone-only tracks, which together comprise the mixed version (see **Table A1 III,** *Audiovisual Material Mentioned in 3.3*: HK_RecMixPO_w & HK_RecMixCMO_w). It is also worth mentioning at this point that in the mixed version, a considerable amount of low-end information is audible; this is due to the fact that this mix was made for the player to include in their portfolio whilst exploring an alternative manner of mixing this instrument in a solo performance, as such one of the piezo pickups (Piezo N2) was run through Analog Obsessions' Lovend & Brainwork's Bx_Subfilter plugins, to generate additional bass information.

3.4 Estonian Bagpipe / Torupill

One other use case for these pickups I wanted to discover was through an instrument that wouldn't be associated with piezoelectric pickups easily: the Estonian Bagpipes or Torupill. The recording took place on the February 25th, 2024, and the instrument was performed by Kadri Allikmäe. The tune is called Polka and can be traced down in the Finnish language recording archive (Metsniit, 1922). In the recording process, I tried several placing options for the piezoelectric pickups; however, the only placement where I managed to get consistent and tangible results was the left side of the bag itself (see EB_Torupill_9544_h). Alongside the piezoelectric pickups, I have used a Schoeps small diaphragm omni microphone for the instrument itself and a Shure SM57 for the drone pipe. The piezo placement provided me with the "fretting sounds" of the instrument as well as a reasonable amount of low-frequency information. The dry recordings can be heard in (see **Table A1**

IV, *Audiovisual Material Mentioned in 3.4*: EB_Torupill_Piezo50mm_1_w, EB_Torupill_SOmni_1_w, EB_Torupill_SM57_1_w) and be visually compared in (see **Table A1 IV,** *Audiovisual Material Mentioned in 3.4* : EB_Torupill_Piezo50mm_1_p, EB_Torupill_SOmni_1_p, EB_Torupill_SM57_1_p). From these recordings we can deduct that the clearly audible "fretting sound" of the flute part of the bagpipe, and the lack of high frequency information heard in the piezo recordings are the main differences in terms of audio content between the conventional microphones and the piezoelectric pickups. This, usually not heard of "fretting sound", helps in the mixing process to add an additional layer of rhythm and movement. It is also worth mentioning that whilst the piezoelectric pickup has a reasonable amount of low-end information, particularly in the 20-200 HZ range, the SM57 and the Schoeps both have a more uniform and clear low-end response thanks to the propagation of the drone signal through air, which through the internal resonance of the instrument became weaker and less clear. Given the more "muddy" bass information found in the piezo recording, it could be deduced that its main use case perhaps wouldn't be bass re-enforcement. These characteristics also helped shape the outcome of the final mix I did for the recordings (see **Table A1 IV,** *Audiovisual Material Mentioned in 3.4*, EB_Torupill_Mixdown_w) Separated spectrogram images and audio exports of the stems of the said mix (see **Table A1 IV,** *Audiovisual Material Mentioned in 3.4*, EB_Torupill_Mixdown_OmniMicOnly_p, EB_Torupill_Mixdown_PiezoOnly_p, EB_Torupill_Mixdown_OmniMicOnly_w, EB_Torupill_Mixdown_PiezoOnly_w) also show that the aforementioned qualities have been either masked or amplified in order the create the best balance possible. It is also worth mentioning that, in order to create the wide and grand Torupill sound, the drone pipe was overdubbed (see **Table A1 IV,** *Audiovisual Material Mentioned in 3.4*, EB_Torupill_DroneRein_w) and used as reinforcement, alongside the conventional microphones and piezo recordings. The drone reinforcement recording was run through Bx_Subfilter & Analog Obsessions' Lovend plugins. Generating additional bass information, respectively at 48 & 96 Hz, to create a big and deep bagpipe sound that alone could fill the frequency spectrum.

3.5 Piano

To demonstrate another example of how these pickups can be utilized in recording and perhaps in live sound situations, I have recorded an Estonia-brand grand piano. The recording session took place on the 21st of February 2024, and the piano rendition of the song “Everything in Its Right Place” (ISRC: GBAYE0000810) by Radiohead was performed by Mr. Taras Shkoliarenko. The recording featured an AB pair of small diaphragm omni microphones as well as four piezoelectric pickups taped to various places on the piano. (see **Table A1 V,** *Audiovisual Material Mentioned in 3.5* : PR_9504_h) Of the resulting recordings with piezo pickups, only one of them had sufficient audio information to be used as a viable example of how these components can be beneficial. This being the second furthest one from the player (see **Table A1 V,** *Audiovisual Material Mentioned in 3.5 for a close-up:* PR_9502_h & *for overall positioning*: PR_9504_h). One limitation I faced during these recordings was the fact that these pickups could not be mounted better to the piano since:

a) The piezoelectric pickups would require a more intrusive installation method to yield the best results, and this wouldn’t be applicable to the instrument in question.

b) The piano was already strung and tuned, which rendered it impossible to access much of the soundboard.

The Recordings can be compared audibly (see **Table A1 V,** *Audiovisual Material Mentioned in 3.5* PR_AB_w & PR_Piezo_w) and visually (see **Table A1 V,** *Audiovisual Material Mentioned in 3.5* : PR_AB_p & PR_Piezo_p). One main difference is the resonances of the instrument (and the wood it is comprised of), which are much more prominent in the piezo recording than in the AB recording.)

This recording, having recorded big bands and orchestras live before, gave me the idea that if implemented properly, piezoelectric pickups might have use potential in the field of live recording, where instrument bleed can be an issue.

3.6 Drum Kit Components

Recording drums using piezoelectric pickups has been an idea that I found to have a lot of potential. I had the chance to do two experiments in this subject, both of which resulted in some failures and some valuable information. My main takeaway would be that, in the world of drum recording, piezoelectric pickups occupy a curious niche. Their strength lies in isolating nuanced vibrations. By placing a piezo pickup on a drumhead, for instance, the engineer can delve into a world of untapped tonal potential. The pickup acts like a magnifying glass, revealing an array of sonic possibilities that might go unnoticed by the human ear or a conventional microphone.

The first test I did in this field was on the 26th of January, 2024. During a recording session under the supervision of my mentor, Mr. Christoph Schultz, I attempted my first full drum kit recording using piezoelectric pickups. The experiment halted rapidly as most of the pickups broke apart (mainly from the solder joints on the disks), and as such, the recording was stopped. This unexpected result came about as a natural consequence of the nature in which drums operate. The crucial caveat which was unveiled was that piezo pickups are ill-suited for the raw power and dynamism of a full drum performance. In the aforementioned recording session, the piezo pickups simply couldn't withstand the forceful energy exerted by the drummer. The sheer impact of the sticks, along with the highly resonant nature of drums, were too much for their delicate construction, rendering them unusable. This rendering out of service arrives not only in the form of physical destruction but also in the form of digital distortion or clipping. To elaborate further on the second point of failure, I have previously mentioned in the chapter, Comparison of Different Sizes of Piezoelectric Pickups, that the nature of piezoelectric pickups tends to fall on the quite side of audio equipment. However, with this drum recording, whether it be from the accidental hits these piezoelectric pickups suffer from, or from the resonant frequencies of drums and the resulting clipping that ensues, we have seen a common tendency to create digital distortion and clipping, almost inevitably. Even with the lowest gain settings possible on the analog to digital converters and software that accompany them, these clipping instances were widespread. As such, these results rendered the first experiment a lesson in caution and made it ineligible as source audio material.

Having witnessed these, I have repaired the said piezoelectric elements using longer cables and sturdier solder joints (see **Table A1 VI,** *Audiovisual Material Mentioned in 3.6,* broken pickups to the left & repaired pickups to the right: DR_9450_h) and re-attempted the same test, this time in a tamer and more controlled environment. The second test took place on the 21st of February 2024 and was conducted with a simpler drum set-up (see **Table A1 VI,** *Audiovisual Material Mentioned in 3.6* : DR_9505_h, DR_9506_h, DR_9507_h, DR_9508_h, DR_9509_h) to test out the feasibility of such recording techniques. Of the resulting material, what captured my interest the most was the cymbal sound I managed to get. As mentioned before, piezoelectric pickups do have a magnifying glass-like function for individual kit pieces, and especially with ride cymbals, they have brought out some interesting qualities. (see

Table A1 VI, *Audiovisual Material Mentioned in 3.6*, DR_CymbalPiezo_w, DR_CymbalOH_Mono_w, DR_CymbalPiezo_p, DR_CymbalOH_Mono_p). From the spectrogram images for cymbal recording made by both piezoelectric pickups and conventional omnidirectional microphones, we can see that the piezo recording delivers mostly the sound information below 1500 Hz, whereas the conventional microphone recording shows much more energy at 3500 Hz and above, whilst almost neglecting frequencies below, except for 300-500 Hz area. This difference in characteristics and timbre unlocks various potential use cases for piezoelectric pickups. Such as use in sample packs and virtual instruments.

The same magnifying glass effect can be seen to an extent in two other pieces; snare drum (see

Table A1 VI, *Audiovisual Material Mentioned in 3.6*, DR_SnareSM57_w, DR_SnareBottomPiezo_w, DR_SnareTopPiezo_w, DR_SnareSM57_p, DR_SnareBottomPiezo_p, DR_SnareTopPiezo_p), and the kick drum (see

Table A1 VI, *Audiovisual Material Mentioned in 3.6*, DR_KickRE20_w, DR_KickPiezo_w, DR_KickRE20_p, DR_KickPiezo_p).

3.7 Human Voice

Another potential use case for piezoelectric pickups that I wanted to discover was their potential implementations in human voice recording. The findings, coupled with some research into the previous works in the field, have yielded what I find to be some interesting results. During the testing process, I recorded my voice using two conventional Mics: one small diaphragm omnidirectional condenser microphone, one large diaphragm cardioid condenser microphone, and a 50mm piezoelectric pickup. The recording was made whilst the piezo pickup was being pressed firmly against my Adam’s apple, where I deemed the vibrations to be most prominent. (see

Table A1 VII, *Audiovisual Material Mentioned in 3.7*, HVR_9523_h).

One angle I wanted to explore with this test was to understand how we hear our own voices, and it can be said that “the perception of a human’s voice can be divided into three main components:

1. Direct sound transmission from the mouth through the air around the speaker’s head to the ear drums (direct air-conducted sound transmission).
2. Internal sound transmission inside the head via bones and skull to the cochlea (bone-conducted sound transmission).
3. Reflections of one’s own voice from acoustically relevant surfaces in the surrounding environment (indirect air-conducted sound transmission).” (H.Lehnert & F.Giron, 1995) as cited in (Pörschmann, 2000, s. 1038)

When we talk about how one hears one's own voice, it is important to keep in mind that “estimations which were derived from different investigations suggest that the perceived loudness of the bone-conducted sound is of the same order of magnitude as the one of the air-conducted sound.” (Békésy, 1949) as cited in (Pörschmann, 2000, s. 1038). To further support this, previous experimentations in the field “measured a decrease of 6 dB in the loudness level of the persons’ own voices due to the elimination of the air-conducted sound.” (Békésy, 1949) as cited in (Pörschmann, 2000, s. 1040) and from this, it was “concluded that the perception of bone-conducted and air- conducted sound are of the same order of magnitude.” (Békésy, 1949) as cited in (Pörschmann, 2000, s. 1040)

One goal I aimed towards was to replicate the human perception of one’s own voice, which I tried to accomplish through mixing. Keeping in mind that human voice perception is made up of equal parts air-conducted sound, and bone-conducted sound, I have made two mixes, the first of which (see

Table A1 VII, *Audiovisual Material Mentioned in 3.7*, HVR_Mix1_InternalVoice_w, HVR_Mix1_InternalVoice_p) is equal parts piezo and conventional microphones (equal parts referring to equal loudness in terms of LUFS) and the second one ((see

Table A1 VII, *Audiovisual Material Mentioned in 3.7*, HVR_Mix2_InternalVoice_w, HVR_Mix2_InternalVoice_p) where I listened to my own speaking voice and tried to replicate as closely as possible.

One other observable result of the piezo recordings is the audible and visible cut-off above 4000 Hz (see

Table A1 VII, *Audiovisual Material Mentioned in 3.7* HVR_50mmPiezo_1_p, HVR_50mmPiezo_1_w).

As great as the conventional microphone recordings are for mixing purposes and are closer to us, to our real-life auditory experiences, the kind of recording and mixing sessions, taking advantage of piezoelectric pickups, might prove valuable in the realm of film and voiceover, where one might want to try to replicate the one's inner voice.

4 Creative Use Cases

4.1 Using Piezoelectric Pickups as Speakers

Among other things, the purpose of this experiment was to discover the degradation possibilities of piezoelectric pickups when used as speakers rather than sound-gathering sources. Sound degradation, i.e. “the condition in which one or more of the required performance parameters fall outside predetermined limits, resulting in a lower quality of service” (National Communications System Technology and Standards Division, 1996, s. D9) is a desired and often pursued sound design tool. Whether it be via implementation of vintage audio equipment & their respective emulations or via various impulse response players, plug-ins aimed at achieving similar effects (bit crushers, ring modulators etc.), the goal is to achieve “graceful degradation” (National Communications System Technology and Standards Division, 1996, s. G4). As such, the purpose of this recording session was to emulate a very resonant and low-quality speaker using these components. The song “Ballad” (ISRC: USY282322618) from my album “Thank You for Your Time” (UPC: 198026865465) was used in the experiments as a wide range of frequencies are represented throughout the song. The test was repeated twice with microphones, both in omni and cardioid pickup patterns. The set up for the tests (**Table A1 VIII**, *Audiovisual Material Mentioned in 4.1* CUC_PiezoSpkr_9554_h) was kept stationary between the change of polar patterns to ensure the maximum visibility of changes which might occur in frequency responses. The first observation I made whilst comparing these recordings was the amount of noise accrued by the microphones, as piezoelectric pickups make for very quiet speakers. As such, their size makes it almost impossible to produce any low-end information. In a comparison between the spectrogram images for the recordings and the reference track (see **Table A1 VIII**, *Audiovisual Material Mentioned in 4.1* CUC_PiezoSpkr_RefBallad_p, CUC_PiezoSpkr_Cardoid_p, CUC_PiezoSpkr_Omni_p) it is visible that the low-end information represented in the piezo recording is mostly room noise. Another observation I made (see **Table A1 VIII**, *Audiovisual Material Mentioned in 4.1* CUC_PiezoSpkr_RefBallad_w, CUC_PiezoSpkr_Cardoid_w, CUC_PiezoSpkr_Omni_w) is the resonance occurring in the piezo recordings. While the 3khz & 5khz resonances are common in both recordings, the cardioid recording also tends to emphasize the 9.5khz and 14-15khz intervals of the spectrum.

4.2 Capturing Percussive Sounds for Further Sonic Explorations

Inspired by Blackfly, a “spring activated instrument that delivers a wide spectrum of sonic textures. “ (Electro Faustus, 2014) I have built a percussive instrument with similar features. Using a 50mm piezoelectric pickup, mounted directly into a metal box using epoxy and adding various springs I have not only replicated but also customized (see **Table A1 IX**, *Audiovisual Material Mentioned in 4.2* CPSFSE__9552_h) the sonic possibilities which come with this “metallic swarm generator” (Electro Faustus, 2014). The video recording (see **Table A1 IX**, *Audiovisual Material Mentioned in 4.2* CPSFSE_Showreel_m) aims to show what can be achieved in post-production with only the sounds collected directly from this box. The recording acts as a showreel of using only sounds collected from this replicated “metallic swarm generator” to generate a percussion and harmony part in making of a beat. Even though the video is 14 minutes long, I wanted to capture the whole process without any interruptions, and it can be speeded up or skipped to the very end to hear the final work. It is also worth mentioning that the recordings on multiple occasions yielded similar results as the whole box resonates together to create an instrument-like percussive quality whilst retaining, if chosen, the capacity to provide intimate and “micro” soundscapes from various percussive elements. The sound capturing qualities of the internal piezo microphone can be seen in comparison to both cardioid and omni charactered conventional microphones in the test recording, visible in (see **Table A1 IX**, *Audiovisual Material Mentioned in 4.2*, CPSFSE__9552_h). The results, which can be both audibly (see **Table A1 IX**, *Audiovisual Material Mentioned in 4.2*, CPSFSE_SchoepsOmni_w, CPSFSE_SchoepsCarodid_w, CPSFSE_Piezo_w) and visually (see **Table A1 IX**, *Audiovisual Material Mentioned in 4.2*, CPSFSE_SchoepsOmni_p, CPSFSE_SchoepsCarodid_p, CPSFSE_Piezo_p) examined further with the resources. The first observation I made upon listening and visually examining was the existence of frequencies between 100 -300Hz only in the piezo recording and the complete lack thereof in the conventional microphone tracks.

Such percussive instruments, I believe, could be one of the pillars upon which the experimental use cases of piezoelectric pickups can excel.

5 Challenges-faced and Recommendations

While the exploration through studio recordings yielded valuable insights into the potential of piezoelectric pickups, the process was not without its challenges. This chapter delves into the practical hurdles encountered during experimentation and proposes potential solutions and recommendations for improved operability.

One recurrent issue was the inherently low output volume of piezo pickups. The captured sounds often necessitated significant pre-amplification, raising concerns about potential distortion or signal degradation if a single pre-amp was employed. To address this, a cascading pre-amp configuration could be explored; perhaps utilizing multiple pre-amps and/or active di boxes in series to achieve the desired gain without sacrificing sonic fidelity can be considered an option.

Another challenge involved the placement of piezo pickups. Improper placement due to obstructions or lack of pre-planning in instrument design could significantly impact the quality and spectrum of the captured sound. This highlights the importance of collaboration between musicians, instrument makers, and sound engineers during the design and production process. For instance, piano soundboard resonance can be mapped beforehand, allowing for the strategic placement of multiple piezo pickups to capture the full sonic range of the instrument before the soundboard is installed and the instrument is strung. Similarly, integrating a dedicated pocket for a piezo pickup into the bag of a Torupill (Estonian bagpipe) could eliminate the need for potentially unreliable tape attachments. Instruments like the Hiiu kannel could benefit from early access to their sound boxes during production for the permanent installation of pickup(s) wired to a jack, offering a more nuanced and spatially accurate representation of the sound.

For drum kits, where piezo pickups might be used on individual components, the first challenge would lie in cable management. Employing heavy-duty, long cables would ensure less breakage; also, managing the cables in a way that minimum stress is put on the cables themselves and solder connections would prove to be very beneficial for the longevity of the piezo pickups. Careful pre-testing is also crucial to determine the optimal placement for each drum component. Of course, in the case of drum components, one major problem that needs to be tackled would be the attachment method. As drumheads are flexible and interchangeable, it would not be sustainable to use any sort of gluing process on them whilst taping them down, which could result in the issues discovered in the next paragraph.

Finally, the importance of secure connections between the piezo pickup and the instrument cannot be overstated. Loose connections inevitably introduce unwanted clicks, pops, and compromised sound capture. My personal experimentation over the years has revealed that epoxy proved to be the most reliable adhesive, offering superior hold compared to superglue (which becomes brittle over time), sticky putty (which dampens sound), and tape (which tends to be unreliable with the amount of contact it provides).

By acknowledging these challenges and implementing the proposed solutions or recommendations, instrument builders, musicians, and sound engineers can unlock the full potential of piezoelectric pickups. This collaborative approach, combining creative exploration with practical considerations, could ultimately lead to a richer and more nuanced sonic experience.

6 Conclusions

One other potential use aspect of the piezoelectric pickups, which I believe merits to be talked about, could be their potential uses within the realm of Next Generation Audio or NGA. Next Generation Audio (NGA) transcends the limitations of traditional channel-based audio formats (mono, stereo, surround sound) by introducing a novel audio production paradigm. This paradigm leverages three distinct techniques: channel-based, object-based, and scene-based audio. The combined utilization of these techniques fosters a richer, more immersive auditory experience, expands creative possibilities, and paves the way for interactive and personalized soundscapes (European Broadcasting Union, 2021). Within the object-based audio, the intimate, magnified, and isolated sound-capturing properties of the piezoelectric pickups could render rather helpful. In essence, central to NGA's object-based approach is the deconstruction of traditional audio mixing. Sounds are no longer solely mixed into a predetermined channel configuration. Instead, they are meticulously grouped or isolated into distinct audio streams, forming what are known as audio objects. These objects can represent individual voices, instruments, specific sound effects (e.g., a passing car), or entire ensembles like a string section or drum kit. These objects are maintained as separate entities throughout the production process, ultimately distributed as individual units. This approach significantly differs from conventional audio production practices, laying the groundwork for a revolutionary shift in how we create and experience sound. (European Broadcasting Union, 2021)

Even though my focus was on the implementations of these elements in the domain of recording arts, I've had a rather informative, informal conversation with fellow sound engineer Viljar Rosin, known, amongst other things, for his work with Puulup!, On 29th of February 2024. During this conversation, he confirmed my suspicions concerning the use of piezoelectric pickups in live situations, mentioning the almost inevitable feedback problems one would face while trying to operate within the vicinity of monitor speakers. He emphasized the importance of using equalizers and even mentioned his method of using an eq, compressing, and then using sharp cuts (high or low, depending on the use case) to prevent feedback. He also mentioned the lurking danger of receiving feedback from a subwoofer and advised placing piezo pickups far from subwoofers, particularly when intended for a bass-heavy use scenario (such as a stomp boxes).

The research aimed at identifying unique sonic characteristics, particularly the ability to capture subtle details. This suggests intriguing possibilities in film audio and foley. Piezo pickups could be strategically employed for traditional recordings or integrated within specific scenes. Their capacity to emphasize percussive elements or capture subtle sounds has the potential to open doors for creative sound design and a more immersive cinematic experience.

In conclusion, this work intends to spark discussion and inspire further exploration of piezoelectric pickups beyond their traditional uses. While challenges arose concerning output level, placement, and secure attachment, the proposed solutions and recommendations offer a foundation for more robust and versatile applications. Ideally, these possibilities warrant further investigation through collaborations between sound designers, filmmakers, and piezo pickup manufacturers. Such partnerships could explore these possibilities and refine the technology for film-specific applications.

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Appendix

I. Referenced Audiovisual Materials

Table A1 I, *Audiovisual Material Mentioned in 3.1*

File Reference	Link
FT_SOmni_1_p	https://drive.google.com/file/d/1LBA_PnTcDuPTzsrO1db2c3pevFofg_hh/view?usp=share_link
FT_50mm_1_p	https://drive.google.com/file/d/1UO3QMS6K0dQv9oXaYTX8ayDWBptZ9Yzf/view?usp=share_link
FT_35mm_1_p	https://drive.google.com/file/d/1qi33xL_ZEJRbbx91zFAQ7zJRaor9y3NW/view?usp=share_link
FT_27mm_1_p	https://drive.google.com/file/d/1u4iHb0iYCW6-DfeEE4vwaphaIkuHkYRF/view?usp=share_link
FT_20mm_1_p	https://drive.google.com/file/d/1-rYPap1_CkdjP6GgpH9WWiLuGcc-RmvP/view?usp=share_link
FT_18mm_1_p	https://drive.google.com/file/d/1lKYGTFNWnOizJ5DUoOc9OX3e5BKFs-nT/view?usp=share_link
FT_15mm_1_p	https://drive.google.com/file/d/1EHhjhpOiLox3JdYVTaf5bIEj59_k4bFC/view?usp=share_link

Table A1 II, *Audiovisual Material Mentioned in 3.2*

File Reference	Link
OM_BazenCoda_w	https://drive.google.com/file/d/1frpmrFXRtW9PT3J4-4nx8QtujvXcX56g/view?usp=share_link
OM_BazenCoda_p	https://drive.google.com/file/d/1Y7MUClderwNoClhVZ1vT4VsJ-d8_pMhP/view?usp=share_link

File Reference	Link
OR_Piezzo_w	https://drive.google.com/file/d/1ZH8sOJfczyl9X5lrnny8a907QQlczPKR/view?usp=share_link
OR_Piezzo_p	https://drive.google.com/file/d/1CV_ZZoK8UcOjfGQo-yhRZMWgfilteqI2/view?usp=share_link
OR_SM57_w	https://drive.google.com/file/d/1KIs7wmQBnU7F5hJhksZuHFzdtmdKe-Y_/view?usp=share_link
OR_SM57_p	https://drive.google.com/file/d/19GkpKoek9zPAkrktGw9RwxMivvnt2VTT/view?usp=share_link
OM_BazenCoda_w	https://drive.google.com/file/d/1frpmrFXRtW9PT3J4-4nx8QtujvXcX56g/view?usp=share_link

Table A1 III, *Audiovisual Material Mentioned in 3.3*

File Reference	Link
HK_RecMixCMO_p	https://drive.google.com/file/d/1_1YyuguEILuFB8aKPdzkV3nSjJpvOD5r/view?usp=share_link
HK_RecMixCMO_w	https://drive.google.com/file/d/1cbmou5pOk2uIF2GHlP4d0b1KDky8X9XS/view?usp=sharing
HK_RecMixPO_p	https://drive.google.com/file/d/1lCig03yFjT2kMFuYMhXIhabPp_Oxr5lX/view?usp=sharing
HK_RecMixPO_w	https://drive.google.com/file/d/1mKdQOhNGLkZGRdgv2xNYPU7PUwZhfO9r/view?usp=sharing
HK_RecordingMixed_p	https://drive.google.com/file/d/19iMLKnihGHnqBCN619Yu3aHkIHeDtXFz/view?usp=share_link
HK_RecordingMixed_w	https://drive.google.com/file/d/1I58dlD8fcWasgrBFZ1Q4uHZs7rp74ng3/view?usp=sharing
HK_9559_h	https://drive.google.com/file/d/19t8uNINJkdj3w161ulbt-wsD_FnY4K6_/view?usp=share_link

File Reference	Link
HK_9560_h	https://drive.google.com/file/d/1ANeQsKe9QfPq6ohcctBzj47Qj8xlXqy9/view?usp=share_link
HK_RecPiezoN1_1_p	https://drive.google.com/file/d/1bLFzTvTrmdcqSE2HGmj7tpCEVvw-lCgL/view?usp=share_link
HK_RecPiezoN1_1_w	https://drive.google.com/file/d/1TWTkUPDKMSJUMeNRYd88Uz7YiHdacwdX/view?usp=sharing
HK_RecPiezoN2_1_p	https://drive.google.com/file/d/1Rh_aOBFcOWZ7BHuHDsgQaGK4iE66RMmU/view?usp=share_link
HK_RecPiezoN2_1_w	https://drive.google.com/file/d/180IaJ6Xsi3cYNGqrap2VNz4iJyV10BAy/view?usp=sharing

Table A1 IV, *Audiovisual Material Mentioned in 3.4*

File Reference	Link
EB_Torupill_9544_h	https://drive.google.com/file/d/1GL0PZg5oVadUSl-O_dfxXpqKDxXS_tO1/view?usp=share_link
EB_Torupill_Piezo50mm_1_p	https://drive.google.com/file/d/1n59B0FCS4reLwwWDaY6YllBzWEqi-gOK/view?usp=share_link
EB_Torupill_Piezo50mm_1_w	https://drive.google.com/file/d/1vjcH8MIMATYH4LwwoE1-qC6S8S3ltJxj/view?usp=sharing
EB_Torupill_SOmni_1_p	https://drive.google.com/file/d/1XTbCtxwg0ltbuhoC7Lr1CU1acmHGe2b-/view?usp=share_link
EB_Torupill_SOmni_1_w	https://drive.google.com/file/d/15UKcFSDdBJ_iHts-rBPRxl1Zzp7Je_wx/view?usp=sharing
EB_Torupill_SM57_1_p	https://drive.google.com/file/d/1UEfa7zsiOLQDmrR76yi5c68_sFgf7adE/view?usp=share_link
EB_Torupill_SM57_1_w	https://drive.google.com/file/d/1GEzOIwXLkIiNdjhIJBVCjohVrj48wHqF/view?usp=sharing

File Reference	Link
EB_Torupill_Mixdown_w	https://drive.google.com/file/d/1D5B0McguU71PPgYZpgQerz0AFPbLn9-a/view?usp=share_link
EB_Torupill_Mixdown_p	https://drive.google.com/file/d/1OnIorznDrZctrShDbEgoWtgp_aBBEdnT/view?usp=share_link
EB_Torupill_DroneRein_w	https://drive.google.com/file/d/1-vgWc01BYK3WBauiyERWMSOEeZL5lXQZ/view?usp=share_link
EB_Torupill_Mixdown_OmniMicOnly_p	https://drive.google.com/file/d/15cpVLaAKnjSpnxOeVWCiNJFy4CMXSCWI/view?usp=share_link
EB_Torupill_Mixdown_OmniMicOnly_w	https://drive.google.com/file/d/1WCJfADQghxfIpRAc9Faz2ZkSLGX1nxWj/view?usp=share_link
EB_Torupill_Mixdown_PiezoOnly_p	https://drive.google.com/file/d/1RY_0MxsyMwXeEXkz7zsK3WOmpaM5gDi7/view?usp=share_link
EB_Torupill_Mixdown_PiezoOnly_w	https://drive.google.com/file/d/1iiQ7od3B5euUp913AUP9MIE71Ie2fVbv/view?usp=share_link

Table A1 V, *Audiovisual Material Mentioned in 3.5*

File Reference	Link
PR_9502_h	https://drive.google.com/file/d/18D50iwdDj8yDunY_zyIAJCQmddA36bcv/view?usp=share_link
PR_9504_h	https://drive.google.com/file/d/1pgd_6--F2gK4m1k_1jjxBsgSSvLoQtSH/view?usp=share_link

File Reference	Link
PR_AB_p	https://drive.google.com/file/d/1oK1rjjNecekrPBjhjpwXB7baUcjVNS0H/view?usp=share_link
PR_AB_w	https://drive.google.com/file/d/1agIIsq3m3Ph4d_VNM5UM1LDyY2rqfV56/view?usp=sharing
PR_Piezo_p	https://drive.google.com/file/d/1NTkVIaEbh2iFL0EUdwAfrhq6cAJumKOT/view?usp=share_link
PR_Piezo_w	https://drive.google.com/file/d/1LuemX6qf_VBgKM5Mhae6bIpRdir6GfMe/view?usp=sharing

Table A1 VI, *Audiovisual Material Mentioned in 3.6*

File Reference	Link
DR_9450_h	https://drive.google.com/file/d/1YB-1y5O26ueriLwCnB6eA69WYPoMunBD/view?usp=share_link
DR_9505_h	https://drive.google.com/file/d/16LyVkvPu6ttAJs49UlZ-rCRf2TwECIzU/view?usp=share_link
DR_9506_h	https://drive.google.com/file/d/1h6CYXi4obf8FqE9nGUYrhk5iFyo1K7Qh/view?usp=share_link
DR_9507_h	https://drive.google.com/file/d/1y0utw-OFCZuG6YKYaHYOOLYmfdLspkr2/view?usp=share_link
DR_9508_h	https://drive.google.com/file/d/1iRdYMUPMpEvQpJz8KrR7O9mKl4oej6n-/view?usp=share_link
DR_9509_h	https://drive.google.com/file/d/1ee8pWngxhp2lfwKbdYrt_hsZPx4bGVC9/view?usp=share_link

File Reference	Link
DR_SnareOH_w	https://drive.google.com/file/d/19u0OUIFU46Wx6FchgG9MLoR41VN7ZzVx/view?usp=share_link
DR_SnareSM57_w	https://drive.google.com/file/d/12n7ZMo2iA81506i9oSjulOPi0t0M2uG1/view?usp=share_link
DR_SnareBottomPiezo_w	https://drive.google.com/file/d/1T8yZg2XccLOITjnD9M7eCS45ppC_KvIy/view?usp=share_link
DR_SnareTopPiezo_w	https://drive.google.com/file/d/1Hyjro95hwHXhB0xjvBM7MpJ4tI47lTLB/view?usp=share_link
DR_KickRE20_w	https://drive.google.com/file/d/1o9zWGOC-qjJOT2G2GJzu-BdVZknHpSe-/view?usp=share_link
DR_KickPiezo_w	https://drive.google.com/file/d/1BhLSilBQUDXdbfPkH4H9T_E72fJ9aQ_t/view?usp=share_link
DR_CymbalOH_Stereo_w	https://drive.google.com/file/d/1OYxvkvbG5Yr97opaKdljeIRYFUy0jOFG/view?usp=share_link
DR_CymbalOH_Mono_w	https://drive.google.com/file/d/1fiUl8Ougv5cMKlLKP0G3M1NUf-Q-TiiR/view?usp=share_link
DR_CymbalPiezo_w	https://drive.google.com/file/d/15TqCi99btbLso2qF9-2-W8W6UpzFJPFM/view?usp=share_link
DR_SnareOH_p	https://drive.google.com/file/d/1s5ZwVH_itOvDdFjyCnVxm17nRppBL077/view?usp=share_link
DR_SnareSM57_p	https://drive.google.com/file/d/1nR1_rWY5hcjPQ5Pq2wg3i2TbAp1vmQoR/view?usp=share_link
DR_SnareBottomPiezo_p	https://drive.google.com/file/d/1tnTLdc5EKCB3HzswjYVAe49I-G7vmr0d/view?usp=share_link

File Reference	Link
DR_SnareTopPiezo_p	https://drive.google.com/file/d/1s4geecYJk79ILrVa28NKXLQsj_YJAtTa/view?usp=share_link
DR_KickRE20_p	https://drive.google.com/file/d/1gTasq_mPxg-e-m29PFI_mMgDbJPZ3g8m/view?usp=share_link
DR_KickPiezo_p	https://drive.google.com/file/d/1U4qGtTUX7cwIDGgmNg006VgeFCvq-wkS/view?usp=share_link
DR_CymbalOH_Stereo_p	https://drive.google.com/file/d/1HCpYfMNOstT5pY4yHUYKRv55YV9GcoIV/view?usp=share_link
DR_CymbalOH_Mono_p	https://drive.google.com/file/d/1ndmTPhg3L2LVAKWgixD26jNukiue0S-a/view?usp=share_link
DR_CymbalPiezo_p	https://drive.google.com/file/d/1lL3pLPZQg5b2ymVUasmmaIUUw_xJCAii/view?usp=share_link

Table A1 VII, *Audiovisual Material Mentioned in 3.7*

File Reference	Link
HVR_50mmPiezo_1_w	https://drive.google.com/file/d/16mtcESXRERbwmwPUZ4Bziy7hubamQXnw/view?usp=share_link
HVR_TLM103_1_w	https://drive.google.com/file/d/1SfvKXeuYHCQehYPruM-gZc2Euh5_cr-r/view?usp=share_link
HVR_SchoepsOmni_1_w	https://drive.google.com/file/d/1CB7Mk2Kf8iS3uYkeYZNjkUlTvekeIpl0/view?usp=share_link
HVR_50mmPiezo_1_p	https://drive.google.com/file/d/1OfS7vGaiHywZqTfgRl5w5_n2BMa_jYZ0/view?usp=share_link

File Reference	Link
HVR_TLM103_1_p	https://drive.google.com/file/d/1U-vUvgAeuf_oIayELTuIw17fp3z3o4Q1/view?usp=share_link
HVR_SchoepsOmni_1_p	https://drive.google.com/file/d/1O0UHEOOiubZiPX7DuT1jL6A_RW7Fu9oM/view?usp=share_link
HVR_9523_h	https://drive.google.com/file/d/1gUDTftyWBC_rIH-jYwg9PRt-_RrJtj2v/view?usp=share_link
HVR_Mix1_InternalVoice_w	https://drive.google.com/file/d/16nl5yl9wMc3oFJUt5DO5v2lRm4bwUE-w/view?usp=share_link
HVR_Mix1_InternalVoice_p	https://drive.google.com/file/d/11hulWj9uiA84CnEIvYMIm2oRsFlJrNUg/view?usp=share_link
HVR_Mix2_InternalVoice_w	https://drive.google.com/file/d/1N3pUPDAAA4E7qUa7wlo6-UX7gTMznToT/view?usp=share_link
HVR_Mix2_InternalVoice_p	https://drive.google.com/file/d/1LrGnCC38oOoOuQ07sjVl1HVaObQOOOq7/view?usp=share_link

Table A1 VIII, *Audiovisual Material Mentioned in 4.1*

File Reference	Link
CUC_PiezoSpkr_RefBallad_w	https://drive.google.com/file/d/1o2fsE-jDYMHror6rZMqdtygyOfBjc0Rg/view?usp=share_link
CUC_PiezoSpkr_Cardoid_w	https://drive.google.com/file/d/1NKSjVgy5xQr3a58NW6asX7wqGKcb_6DT/view?usp=share_link
CUC_PiezoSpkr_Omni_w	https://drive.google.com/file/d/1O1Lq4CK5V-XWWaVxKSDAZuwW68rYdDLz/view?usp=share_link
CUC_PiezoSpkr_RefBallad_p	https://drive.google.com/file/d/1IKvkyxS1m2pGrKDg5-V4BsxEq3289UzP/view?usp=share_link

File Reference	Link
CUC_PiezoSpkr_Cardoid_p	https://drive.google.com/file/d/11zZAQCmI_v9V1LT2eBS_pbpQXz1oJzCN/view?usp=share_link
CUC_PiezoSpkr_Omni_p	https://drive.google.com/file/d/1jiIHitcBn52oxlUDCghrUskR7anP69X0/view?usp=share_link
CUC_PiezoSpkr_9554_h	https://drive.google.com/file/d/1auGkUpi6QcbtmwJYc1GNNDV-huwfaUdF/view?usp=share_link

Table A1 IX, *Audiovisual Material Mentioned in 4.2*

File Reference	Link
CPSFSE__9552_h	https://drive.google.com/file/d/124kjU7Yi6NcMmeN945XXwDtLRLVmsgpX/view?usp=share_link
CPSFSE_Showreel_m	https://youtu.be/LqOREj6BD2Q
CPSFSE_SchoepsOmni_w	https://drive.google.com/file/d/1yWZmlJsXvlJXZbIa9UHgyWhFFzpBaWqo/view?usp=share_link
CPSFSE_Piezo_w	https://drive.google.com/file/d/1XI1j32CNwGlCtO1mOHdeMuizDujc4gr5/view?usp=share_link
CPSFSE_SchoepsCarodid_w	https://drive.google.com/file/d/1DzAZfwqykwH9A4W4tQe7Kt1O7ZV8NC7x/view?usp=share_link
CPSFSE_SchoepsOmni_p	https://drive.google.com/file/d/1i2I0RT60Uphbp-3PJx7dAcblGvls7D5t/view?usp=share_link
CPSFSE_Piezo_p	https://drive.google.com/file/d/1VvIOxkLMDyB73TIIQt01uN7vbPx3rCf8/view?usp=share_link
CPSFSE_SchoepsCarodid_p	https://drive.google.com/file/d/1J8XhABonxnXhdP5G2__LS57dJ1gnt2mm/view?usp=share_link

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