Audio Reconstruction of Mechanically Recorded Sound by Digital Processing of Metrological Data

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Abstract
For the bulk of recorded sound history the audio information was stored in mechanical media, such as a phonograph record or wax cylinder, via undulated surface incisions (grooves). The grooves' shape and position can be reconstructed without mechanical contact by using precision optical metrology tools. The surface map thus obtained can be digitally processed to remove noise artifacts due to damage and wear, and to convert the groove positional information into audio format. The viability of this approach was recently demonstrated on a 78 rpm shellac disc using two dimensional image capture and analysis methods [1]. The present work expands on these results. A three dimensional reconstruction of mechanically recorded sound is reported. The surface of the source material, a wax cylinder, was scanned using confocal microscopy techniques and resulted in a faithful playback of the recorded information. The approach holds promise for careful reconstruction of valuable historical recording using full surface information to improve the sound fidelity, as well as means of automated mass digitization. Fast processing is required for the latter application. Methods to accelerate the scan rates, thereby making these techniques practical for use in working archives, are reported.

Introduction

The history of recorded sound can be generally classified into three periods. The first one originated with Edison's invention of reproducible sound and lasted until the mid-twentieth century. The vast majority of sound recordings were captured with mechanical-based media, such as cylinders and discs. The recording process resulted in surface undulations on these materials, which could subsequently be played back. The second period, which lasted until the 1980s, was marked by the usage of magnetic tape and wire. The magnetic media generally provided better fidelity sound capture and wider frequency response range. The mechanical media was still used for mass production of stereo vinyl discs, however the studio masters were usually made on magnetic tape. The current period started with the introduction of the Compact Disk and is characterized by the usage of digitized information. The digital nature of modern sound carriers enables lossless duplication, thereby avoiding many of the problems associated with the analog sound carriers.

The mechanical nature of the carriers used in the first period allows for damage susceptibility in handling, as well as material changes, chemical and biological reactions. The problem is particularly exacerbated for media manufactured from soft materials, such as wax and nitrocellulose acetate cylinders, and instantaneous recordings on discs. The latter were never meant to be played repeatedly.

In this work we have investigated the applicability of the modern surface metrology tools to recover the sound from 78 rpm discs and a Blue Amberol cylinder. All the sound the mechanical carriers contain is encoded in the geometry of the groove shape on the surface. Therefore, by making a metrological map and then emulating the stylus motion on the surface, one can extract the sound. The examples of the tools include digital cameras for two-dimensional (2D) image capture, and optical distance-sensing probes for three-dimensional (3D) surface profiling. The non-contact nature of the tools allows one to avoid further damage to the samples in the process of the sound reconstruction.

In the following, we first describe the features of the method, followed by sound extraction tests, exploration of the scan time optimization, and conclusions.

The metrological (imaging) method

The procedure for sound reconstruction with metrological measurements consists of the following steps:

- Use of two- or three-dimensional data (images) with proper magnification and resolution to measure local groove shape.
- Covering the whole surface of a record with multiple views or data points.
- Combining the individual measurements to make a map of the whole record.
- Extracting the groove shape from the map.
- Modeling (emulating) the stylus motion on the groove to extract the sound waveform.

The general method begins with taking metrological data on sequential parts of the record surface. The simplest case is a digital image taken with appropriate optical magnification to discern the smallest groove undulations. An example image of 78 rpm record surface is shown in Figure 1. One can clearly see the lateral (side to side) groove undulations in the figure.

All the cylinders and some of the discs feature vertical groove modulation, where the sound is encoded in the varying depth of the groove. In such cases the two-dimensional digital images are of little use. One needs a way to measure the heights of different portions of the surface. There are two technologies which have the necessary resolution. With a confocal microscopy probe [2,3], a precise surface height is measured on a given location. By moving the sample and repeating the measurements, one can scan the whole surface and obtain its shape in the form of three-dimensional surface "image". An example scan of a portion of a cylinder is shown in Figure 2.

Another technology suitable for three-dimensional imaging is White Light Interferometry [4,5]. It uses a combination of interferometry, 2D imaging, and vertical scanning to resolve the surface height for each pixel of the image. The test samples looked very promising, but as of this writing we have not yet performed an evaluation of the sound extraction with this technology.

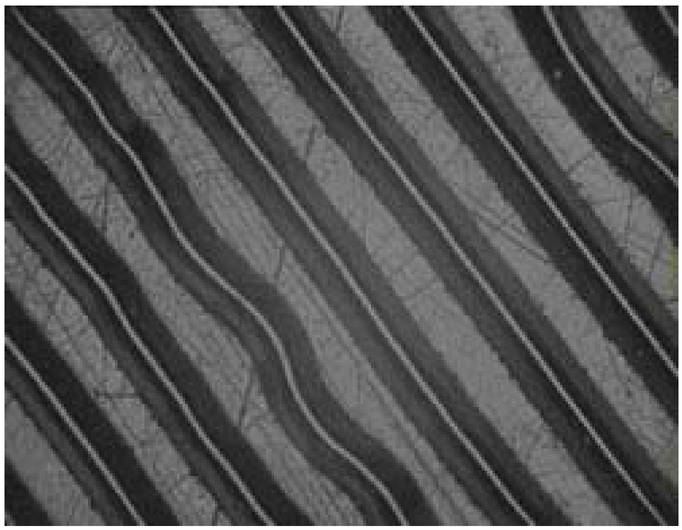

Figure 1. Digital image of the surface of 78 rpm record taken with optical magnification. The illumination is coaxial (the light falls vertically onto horizontal record), therefore only horizontal parts of the record reflect the light back into the optical system. These include the inter-groove surface of the record represented by the wide bands in the picture, and the bottom portion of the groove, represented by the thin lines. The scratches on the inter-groove surface are clearly seen. The size of the imaged surface is 2.35 x 2.19 mm^2.

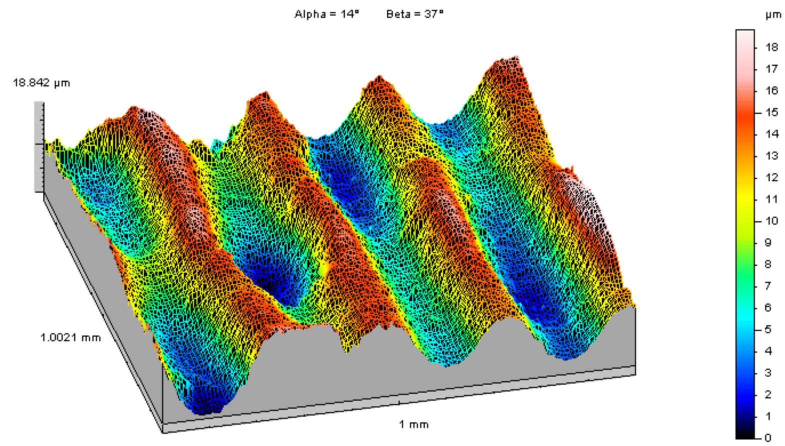

Figure 2. A scan of an Edison cylinder obtained with confocal microscopy. The surface height is color-coded. The groove's up and down undulations are clearly seen. The size of the imaged surface is 1.0 x 1.0 mm^2.

The essential imaging nature of the method leads to the following key advantages over the conventional stylus-based playback:

- The delicate samples can be played without incurring further damage to the record.
- The discrete noise sources, such as dust, scratches and cracks can be resolved during the image processing. They can be subsequently removed, and the affected areas reconstructed by interpolation from the neighboring regions. This is very different from the probabilistic nature of the noise suppression used in modern algorithms [6]. Of course, one can still use the noise suppression tools on the reconstructed sound after a record is scanned.
- The method is relatively insensitive to the exact material composition and color of the record.
- There is a potential for reconstructing broken records.

The consequence of the visual processing is the increase in the amount of data to handle, compared with the stylus-based playback. This affects the scanner design and time performance. We comment on these issues later on in this paper. We now turn to the practical tests of this method.

The Two-Dimensional Proof of Concept Test

This is only a short description of the test. A more detailed writeup is available in a prior publication [1].

The two-dimensional test was done with the "Smart Scope" tool manufactured by Optical Gaging Products (OGP) of Rochester, NY, USA. The exact specifications are available from the manufacturer's web site [7]. In short, the tool is a microscope with a digital camera supplemented by precision motion stages. The optical zoom, motion of mechanical stages and the data acquisition are computer-controlled. A proprietary menu-driven image processing software is supplied as well.

Using the Smart Scope software, we wrote a program to follow the groove on a 78 rpm record. The illumination is coaxial with the optics, therefore the the horizontal areas on the disc, such as the top surface and the groove bottom, appear substantially brighter than the sloped surfaces, such as groove walls, scratches, and dust particles. The program uses the OGP software built-in edge detection tool to find points spaced by about 8 microns along dark-to-light transitions in the search areas. Both left and right edges of the illuminated groove's bottom are targeted. Occasionally the software would also find spurious points along surface defects. All the points are saved in a file and further processed offline.

The main steps of the offline processing are the following:

- The illuminated bottom width is determined from the left-to-right edge distance calculation. The average width is about 7 microns. We remove the points with abnormal value of the width, since they correspond to defects. The points along the original groove prior to the damage were obtained by interpolation from the neighboring regions. This step is a powerful noise suppression feature of the processing. The measurements from both edges are then averaged to improve the accuracy of the groove shape determination.
- The measurements obtained from successive image frames have relative offsets, with a typical scale of about 1 micron. They are due to the finite precision of the mechanical stage motion. We correct for the offsets by shifting the data from an image frame in the radial direction to match the data from the preceding frame. The result is a continuous measurement of the groove shape.
- The groove shape data are differentiated to produce the sound waveform.

Using the process, we scanned a 19-second clip from a 1950 78 rpm record [8]. No special selection motivated the choice of the sample. The record was in fair condition, we did not attempt to clean it. For comparison, we also played the same disc on a stylus-based turntable. It turned out, that the performance was also recorded on a magnetic tape, and later digitally remastered to produce a commercial CD. The resulting waveforms are shown in Figure 3. One can see that the general shape of the waveforms matches very well across the samples obtained with different techniques. The clip from the stylus turntable playback shows more sharp spikes, which correspond to the "clicks and pops" noise typical for old records. Such noise was strongly suppressed in the case of the sound reconstructed with the optical imaging method. However, a wide band "hiss" is also present.

To gain an insight into the noise origin, we looked at the groove shape (the data before the differentiation step) in a musically quiet region of the clip. It turned out that the data were not randomly distributed. Instead, they formed clearly shaped peaks, with a typical size of about 0.2 micron radially and about 100 microns along the groove. Dedicated scans of the (also quiet) sections of the innermost and outermost grooves of the record supported the observation. The amplitude of the hiss was substantially higher, and the frequency spectrum was broader for the outermost groove. This finding is qualitatively consistent with the idea that the same surface defects are present throughout the record, however they cause louder noise at the larger radii due to the larger linear speed of the stylus.

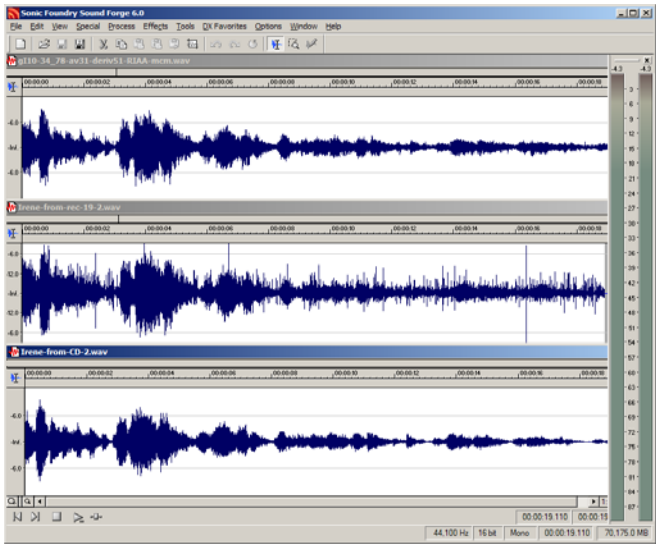

Figure 3. The comparison of the waveforms of 19-second clip from 78 rpm record, obtained with different technologies. The top is from the optical imaging method, the middle is from the stylus-based turntable playback of the same record, and the bottom is from the same performance captured on magnetic tape and subsequently digitally remastered.

The Three-Dimensional Scan of an Edison Cylinder

A more detailed discussion of this study will be available in an upcoming publication [9].

The test was performed with color-coded confocal probe [10]. A portion of the cylinder was repeatedly scanned along its length, with 0.01 degree rotation between the scans. The full circumference of the cylinder was scanned. The rotation step corresponds to 96 kHz sampling in the time domain. The step size along the cylinder axis was 10 microns.

Groove profiles are clearly seen in the scans along the cylinder length. The regions around groove minima were fit to a shape which modeled the known stylus geometry. Data inconsistent with this profile were removed. Using this procedure, groove minima heights were determined.

Ideally, the Blue Amberol is cylindrical in shape. The data from the scan showed, in addition to the audio waveforms, some overall distortion to the object. However, both the groove minima and ridges between the grooves follow the same overall structure caused by these distortions. We subtracted the smoothed groove top (ridge) heights from the minima to avoid introducing low frequency noise into the reconstructed sound.

The groove shape thus obtained was then differentiated and filtered in the frequency domain. The frequencies below 20 Hz and above 5 kHz were suppressed.

We compared the waveform of the reconstructed sound with the stylus-based playback of another cylinder from the same production. The overall structure of the waveforms is very similar.

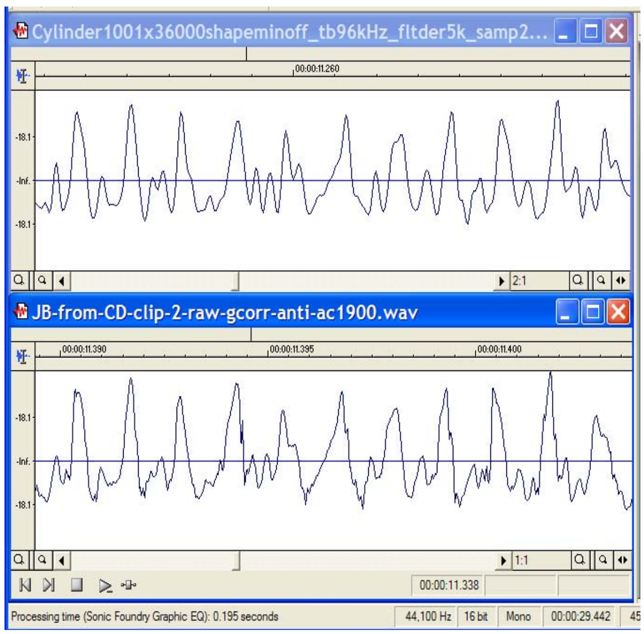

Figure 4. Waveforms from the optical reconstruction method (top) and the stylus based playback (bottom). Only 15 ms portion of the scanned samples are shown.

Scan time optimization

With current digital photography technology, the information readout time represents a major bottleneck. Linear CCD technology is frequently used to achieve fast information retrieval. An image is captured one row of pixels at a time, with simultaneous exposure and readout, achieved by data buffering. In our design of a specialized two-dimensional scanner, we envision using a linear CCD sensor with a continuously rotating record. The image smearing due to the motion is expected to be smaller than the pixel size. The slow rotation speed is compensated by the sensor length simultaneously capturing multiple grooves. This design avoids the complicated mechanics in the case of "stop-and-go" mode. To alleviate the data handling, a real-time edge detection can be used, achieved with specialized image processing hardware. The time estimates indicate that, with such a design, a 78 rpm discs can be scanned in about 10 minutes.

The three-dimensional scanning time depends on the scanning equipment, strategy and media type. This time is in the range of a few hours to a few tens of hours.

Conclusions

We have introduced the method of sound reconstruction from the mechanical recordings based on acquisition and processing of metrological data (images). The non-contact nature of the method makes it suitable for reconstructing delicate recordings. Parts of a broken record can be scanned and then recombined digitally. The transient noise sources ("clicks and pops") are suppressed via image processing.

The scan time is a concern in this method. We have a basic design of a dedicated two-dimensional fast scanning machine. With a scan time of about 10 minutes, it could be used in archives and sound collections to make access copies. The three dimensional scans are substantially slower, but they hold promise for making high-quality preservation copies. Three-dimensional surface profiling methods are used in a variety of industries, and their scanning speeds are expected to improve in the future.

We have performed both two- and three- dimensional proof of concept tests. High quality sound was reconstructed, and instantaneous noise sources suppressed. The sound clips, writeups, and some of the presentations are available on our web site cite [11].

The future work, supported by the Library of Congress, will attempt to address the issues of three dimensional scanning time optimization, and sound reconstruction from significantly damaged samples.

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References

[1] Fadeyev V. and Haber, C., J. Audio Eng. Soc., vol. 51, no. 12, pp. 1172-1185 (2003).
[2] Corle, T.R., and Kino, G.S., "Confocal Scanning Optical Microscopy and Related Imaging Systems", Academic Press, 1996.
[3] Cohen-Saban, J. et al, Proc. SPIE, 4449, 178-183, (2001).
[4] Davidson, M. et al, Proc SPIE, 775, 233-247 (1987).
[5] Caber, P.J., Applied Optics, 32, 3438-3441 (1993).
[6] Simon J. Godsill and Peter J.W. Rayner, "Digital Audio Restoration: A Statistical Model Based Approach", Springer-Verlag, 1998.
[7] Optical Gaging Products, Inc. Web address is www.ogpnet.com
[8] Decca Recording N 76422, "Goodnight Irene", by Gordon Jenkins and His Orchestra and The Weathers.
[9] Fadeyev, V., Haber, C., Maul, C., McBride, J. W., and Golden, M. to be submitted.
[10] We used Model CHR150 probe, manufactured by STIL SA.
[11] www-cdf.lbl.gov/~av .