

Application Note # 26

Selection of Stylus & Cartridge
for
Record Transcription
of
78 RPM & Edison Diamond Disc Records

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5/26/2021

Selection of Cartridge and Stylus for Transcription

Introduction

This work grew out of a discussion with the author of a web site located at: <http://www.amplitudemodulation.com.au/eddisk.html#zfee> with regard to the optimum stylus size for playing Edison Diamond Disc records, technical research in numerous AES (Audio Engineering Society), audio engineering books, and experimental work by the author on hundreds of records.

The selection of the cartridge and stylus for taking the sound from the record groove and converting it to an electrical signal is *critical* to the success of music restoration for a number of reasons:

1. The transcription process cannot damage the sound grooves since the record has value as a piece of history.
2. The process has to extract the maximum signal and the minimum noise from the record groove. Noise is defined as both surface noise and distortion to the original sound.
3. The conversion of sound to mechanical motion used different methods by the music companies which in turn require unique approaches for our work.
4. When the sound is converted from the groove motion to an electrical signal, the frequency content must contain *both* the total range of the music and the noise energy from defects to enable the noise algorithms to effectively restore the music.
5. The transcription should not alter the frequency content from the groove, i.e., the preamplifier has a uniform or flat response for the range of audio *and* noise to at least 40 kHz.

Cartridge Selection Acoustic and Electric Recording

The Acoustic recording method for lateral and vertical groove motion was a *constant velocity* type over the main range of recorded music. The low frequency

end of the music had reduced energy due to the mechanical recording equipment with a natural *turnover to constant amplitude* in the general frequency range of 400 Hz. The specific turnover value differed between companies and over time.

The Electric recording method uses a combination of constant velocity and constant amplitude with the turnover frequency controlled to a tighter value versus the earlier technology.

For constant velocity recording, the use of a magnetic cartridge will provide the best method for playback of the groove for either vertical or lateral motion. The magnetic cartridge has a constant velocity response and when used with the same recording method yields the correct flat frequency response. The original sound from the curve is now available as an electrical signal at the output of the cartridge.

There are many magnetic cartridge manufacturers available and the choice should have the ability to easily change the stylus for the different types of records you want to transcribe.

Errors in Playback from Stylus Shape for Lateral and Vertical

Audio engineers have created a very large amount of information regarding potential sound problems for the complete recording path from the original recording to the playback of the music for the listener. A review of this audio information provides important insight into the best method to playback Diamond Disc records and 78 RPM lateral recordings using the current equipment available. The first question to understand is how does the shape and size of the stylus affect the original recording? One method used is to consider that the recorded sound wave in the record groove has a finite *wavelength*, defined as the distance from the beginning of the sound wave to the end of a cycle. While this definition is correct strictly for sine waves not sound waves; it can be used to estimate the relationship between the stylus size and the maximum recorded frequency in the following manner.

As the radius of the record changes, the velocity of the stylus tip following the sound groove will also change for a constant record speed. For the worst-case situation, consider the velocity at the inner radius and the highest sound recorded. If the length of the wavelength of the sound in the record groove is the same or close to the size of the stylus in contact with the groove, then severe distortion will occur since the shape of the wavelength cannot be accurately traced by the stylus. Although

this concept is a starting point, an approach that considers the distortion with more accuracy is needed since the sound is degraded before the complete loss of the sound.

The general term that is used by the audio engineers to describe the behavior of the stylus as it follows (or traces) the music groove is *Tracing Distortion*. This playback problem is fundamentally caused by cutting the original music groove with a chisel shape (wide for the groove width and then shallow on the edge) while a spherical shape is used to playback or trace the music. The general tracing problem was studied in a landmark technical paper in the Journal of the Acoustical Society of America written by W. D. Lewis and F.V. Hunt in the late 1930's. In this technical paper the exact motion of the stylus was calculated as it followed the groove so that a clear understanding of the distortion caused by the stylus shape and recording process could be mathematically described. After this article was written, a number of researchers used the results to understand the limits in both vertical and horizontal recording. The next section uses an approach by Frayne and Wolfe that builds on the original work by Lewis and Hunt.

Pierce and Hunt Analysis Method

The following information has been based from the book "Sound Recording" by Frayne and Wolfe section 13-7 in their book. This reference should be consulted for greater details if needed for the tracing error. Figure (1) shows a spherical stylus as it travels along a hill and dale record groove from the book. The same picture can be used to describe the lateral motion if the figure is turned 90 degrees.

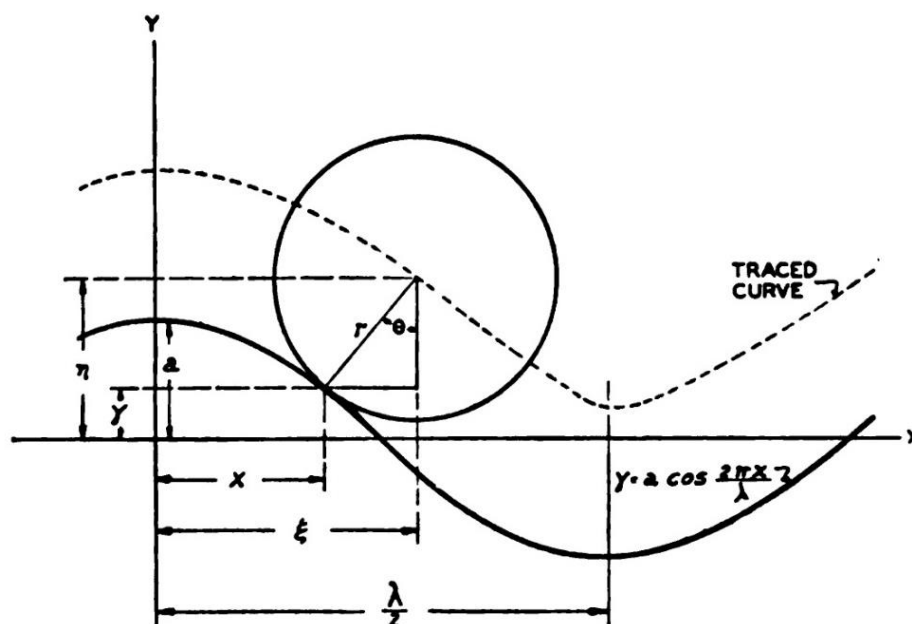


FIG. 13-14. Recorded curve and curve traced in reproduction. (After Pierce and Hunt.)

Figure (1) Stylus as it Travels the Groove

The dashed curve shows the shape seen by the stylus and sent to the cartridge and the solid curve shows the original sound curve cut into the material to form a groove. Notice that the original cosine wave shape traced is distorted because the contact location changes from the bottom of the stylus ($x = 0$) to a side (x) and then back to the bottom. The traced curve has been distorted from the original and the general term is called *tracing distortion or error*. The reference book continues to define the various variables and develops a method to describe the traced curve as a series of complex equations. The authors of the book cite the original work on this subject developed by Pierce and Hunt in the 1930's. For the figure shown in (1), the variables will be defined as used in the book, section 13-7, where:

$r = \text{radius of stylus}$

$\lambda = \text{wavelength of recorded sound}$

$\theta = \text{angle of contact with reference to perpendicular of stylus}$

η and ξ are the stylus coordinates

x and y are the recorded cosine coordinates

$a = \text{amplitude of cosine and } k = \text{a constant}$

The recorded sound curve is: $y = a \cos \frac{2\pi x}{\lambda} = a \cos kx$ eq (1)

$$\xi = x + r \sin \theta \text{ eq (2)}$$

$$\text{and } \eta = y + r \cos \theta = a \cos kx + r \cos \theta \text{ eq (3)}$$

$$\text{Where } -\tan \theta = -ka \sin kx \text{ eq (4)}$$

$$\xi = x + \frac{kar \sin kx}{\sqrt{1 + k^2 a^2 \sin^2 kx}} \text{ eq (5)}$$

$$\eta = a \cos kx + \frac{r}{\sqrt{1 + k^2 a^2 \sin^2 kx}} \text{ eq (6)}$$

These last two equations describe the motion of the stylus as it traces the groove, hence the potential tracing error. More mathematical development occurs in the reference chapter in solving these equations using a Fourier series expansion and then developing results for the harmonic distortion in the sound caused by the playback mechanisms. An important result occurs when the reference book states: “It is evident that the shape of the poind (the traced curve) and hence its percentage harmonic content does not depend on the *actual* dimensions of the original cosine curve and the radius of the tracing circle, but rather its shape depends on the *relative* values of certain of the dimensions. Thus, the shape of the poind can be entirely specified by giving the values of the ratios of (a/λ) and (r/λ) where a is the amplitude of the wave being traced, λ is the wavelength on the record, and r is the stylus-tip radius”.

This result gives us great insight into the correct stylus to use.

The next section in the reference develops a chart that shows total harmonic distortion results for various conditions, namely modulation (lateral or horizontal), stylus radius, amplitude, frequency, and record speed. All of these values can be reduced to a plot of ka vs kr . Where:

$$ka = (2\pi a/\lambda) \text{ and } kr = (2\pi r/\lambda) \text{ eq (7)}$$

The chart of Total Distortion using these values is shown in figure (2).

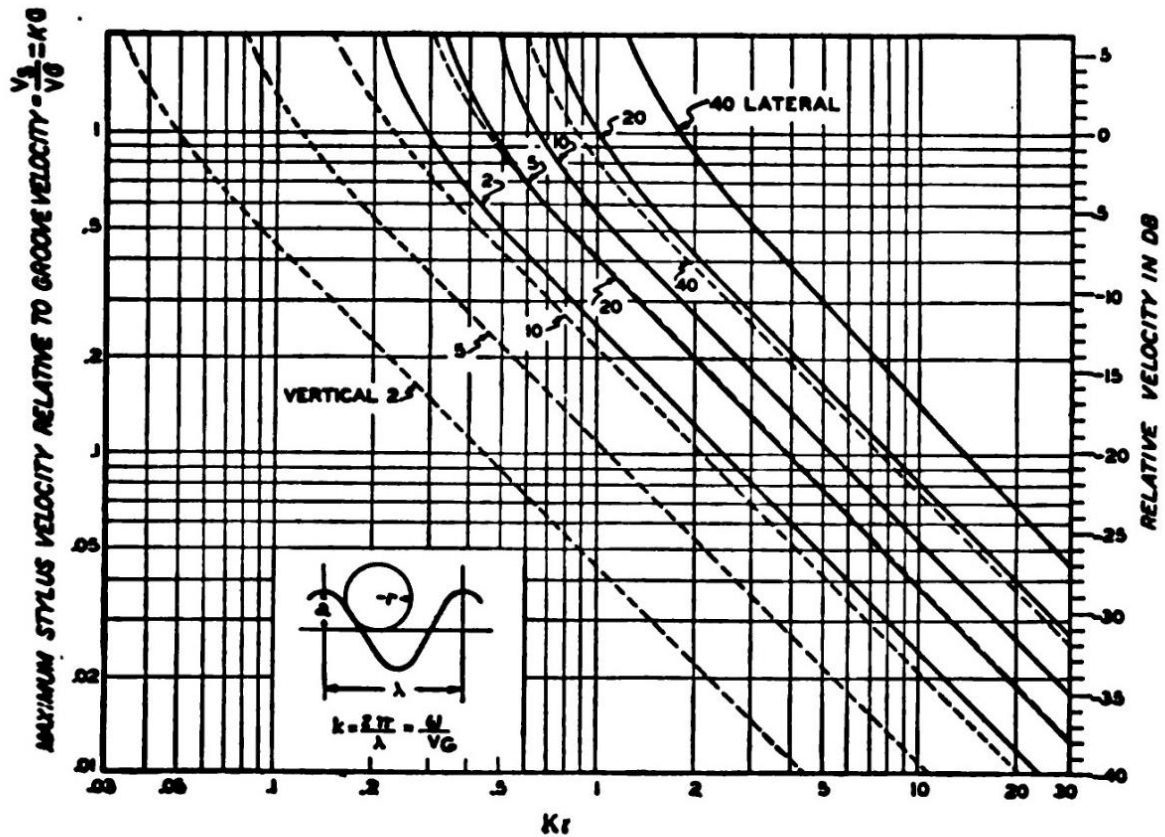


FIG. 13-16. Constant distortion contours for lateral and vertical records. (After Pierce and Hunt.)

Figure (2) Constant Distortion Contours

Notice on the chart that there are lines for both Vertical (Dashed) and Horizontal (Solid) motion and that the vertical values are greater than the horizontal for similar conditions (cancellation of even harmonics occurs for horizontal motion).

The analysis in the book continues with general development of other relationships that can be established with the following important conclusions for the variation of *total harmonic distortion*:

1. Directly with the recorded amplitude for vertical and as the square of recorded amplitude for lateral records, assuming constant frequency, groove speed, and stylus radius.
2. Directly with frequency for vertical and as the square of frequency for lateral, other qualities remaining constant.
3. Inversely as the groove speed for vertical, inversely as the square of groove speed for lateral, other qualities remaining constant.
4. Directly as the stylus radius for vertical, directly as the square of the stylus radius for lateral, other qualities remaining constant.

These relationships can be written with these equations:

$$\text{Distortion of vertical records} = \text{constant} \times \frac{raf}{vg} \text{ eq (8)}$$

$$\text{Distortion of lateral records} = \text{constant} \times \frac{r^2 a^2 f^2}{Vg^2} \text{ eq (9)}$$

Where

$$Vg \text{ (Groove Speed) } \text{inch/sec} = \frac{(2\pi R) \times \text{RPM}}{60} \text{ inch/sec eq (10)}$$

The book concludes with a graph, figure (3), showing Total Distortion verses Recorded frequency for a spherical stylus with a radius of 2 mils and 2 mils of constant amplitude up to 300 Hz and constant velocity above 300 Hz. These values represent some lateral record conditions at the time of writing the book and are different than the Diamond Disc records. Calculations for some records will be done later. The actual values for many 78 RPM records are not available as manufactures used unique values for their records (often they were trade secrets).

Notice on the graph the equation that shows how the amplitude decreases as the frequency rises from 300 Hz (turnover value).

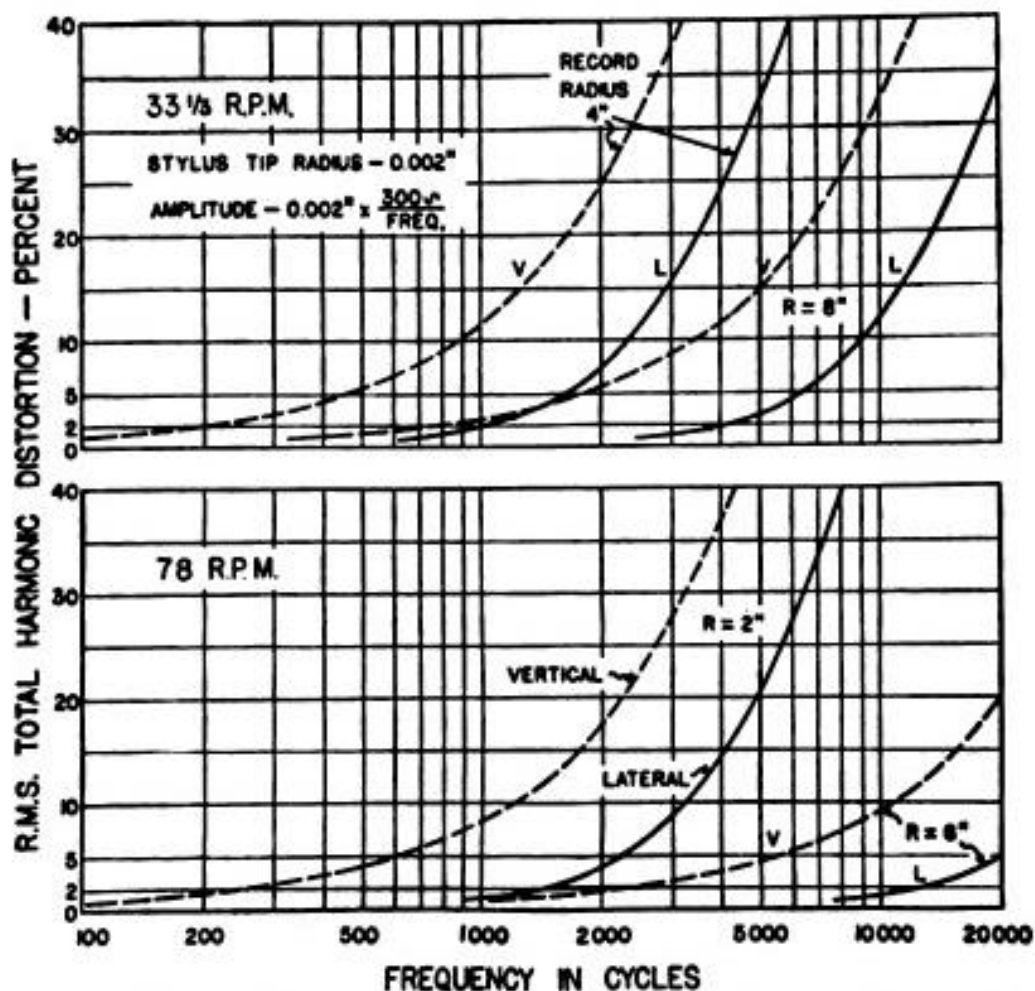


FIG. 13-17. Curves of distortion versus frequency for various recording conditions. (After Pierce and Hunt.)

Figure (3) Distortion for Various Record Radius

Now that this information is available, calculations for harmonic distortion for Edison Diamond Disc Records and 78 RPM records can be performed to understand the effect of stylus size on performance. Two cases for the vertical diamond disc records will be studied using the original stylus shape by Edison and a current stylus used by DJs for LP records. The DJ stylus was selected from experimental studies by the author that have found that a specific current product from the Ortofon company performed very well with the diamond disc records and exceeded the original Edison design for clean sounding music. The lateral records will use a 2.5 mil stylus and a 3.5 mil stylus where the 2.5 mil was originally recommended by cartridge companies for "typical" 78 RPM records and the 3.5 mil was from

experimental studies by the author. Let's first review the original diamond disc stylus design.

Edison Diamond Disc Vertical Modulated Records Stylus Selection

Diamond Discs records used a hill and dale method to store the sound waves in the record groove. This method had been used by the Edison Company for the cylinder records and continued with some changes for the new flat records. Figures (4) and (5) are from the Edison National Park and shows the diamond stylus and the stylus in a record groove.

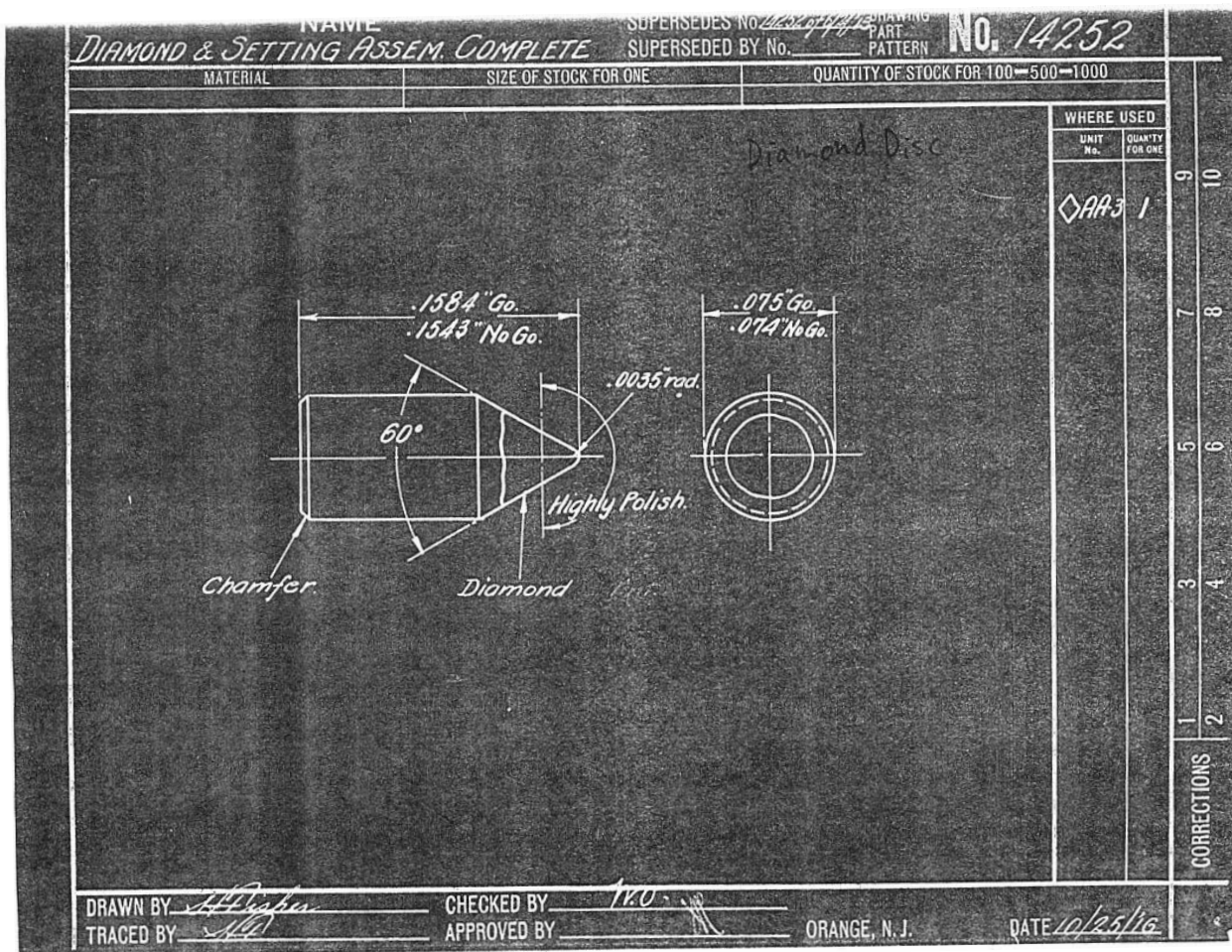


Figure (4) Diamond Disc Stylus

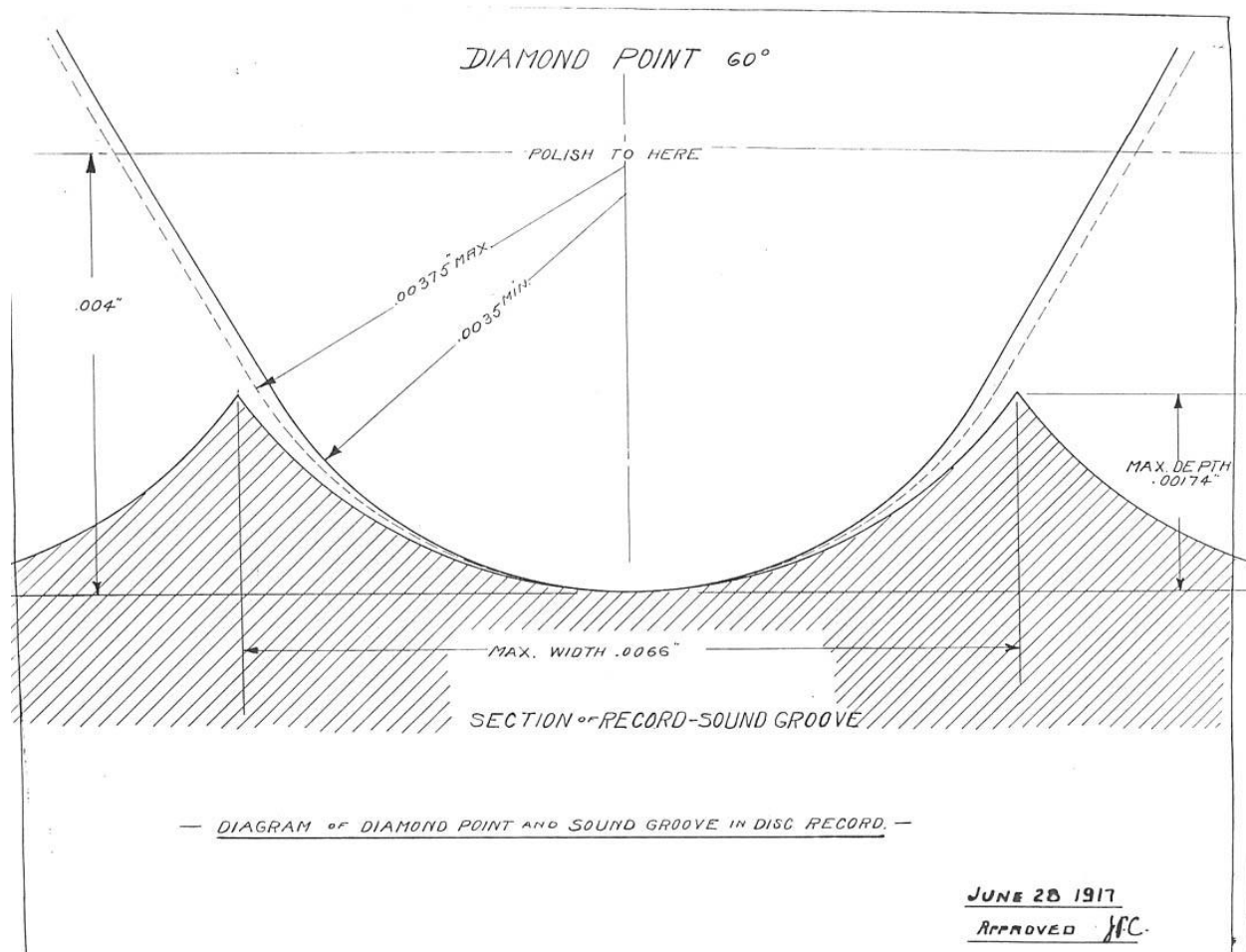


Figure (5) Diamond Disc Stylus in Groove

These two drawings provide important information regarding the correct stylus to use for the records. Since the modulation of the sound is vertical and the maximum depth is 1.74 mils (thousandth of an inch), the midpoint would be half of this value or 0.87 mil and would correspond to no sound. The peak movement then would be ± 0.87 mil which is a very small amount.

The radius of the diamond point as shown fits within the curve of the groove and is designed to ride on the *bottom* of the groove. The music information is contained at the bottom of the groove and the width of the groove will vary as the recording cutter travels up and down. The original groove on the record was cut into a soft master recording using a shape described in Edison Patent number 964,221. This patent explains a new method of recording the sound that deviated from the previous cylinder recordings by using a smaller groove size and smaller depth to improve the performance of the cutter so that the downward and upward cutting

motions would need similar cutting energy. The previous method introduced some distortion by having more sound energy needed to cut down than up.

Figure (6) contains drawings from the patent that shows the reduction in the groove size using the new method with the shown fig.4 the diamond disc groove and fig. 3 the previous groove on the cylinders.

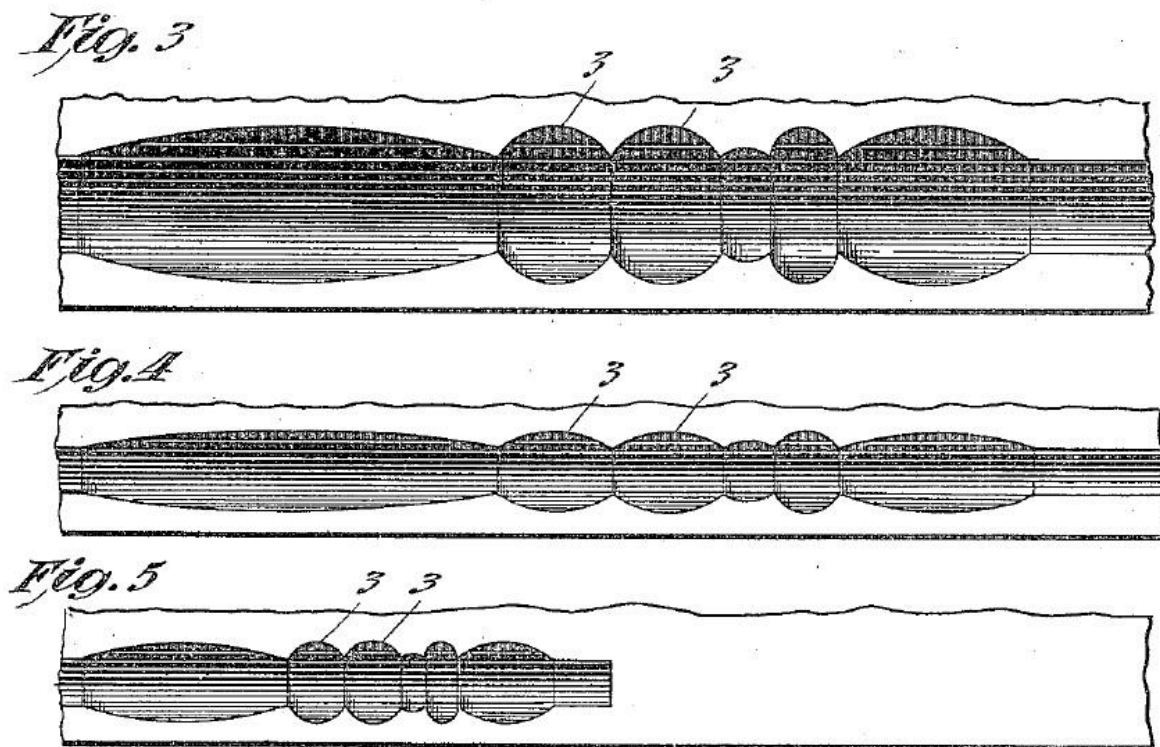


Figure (6) Patent Information

The Edison Music Company, as did the other Music companies, did not publish technical information regarding the details of their record production. Changes occurred due to constant improvement and were always present so that some of the drawings and Patent information can be used today only as a guide.

Since the Diamond Disc phonograph used no electrical amplification until much later at the end of the 1920's the motion of the sound grooves had to be amplified via mechanical methods. Within the Edison reproducer was a lever that amplified the groove motion coupled to a heavy floating weight that when moved by the stylus motion would in turn move a special diaphragm to produce sound waves. The force applied to the stylus was approximately 190 Grams and could be more or less for different models. This heavy force moved by the groove would then

produce a significant amount of sound energy for the record listener. Because of the large stylus force, Edison used a rather large diamond point in a spherical shape to provide a reasonable life time for the records, as the pressure on the record groove is directly related to the applied force and the size of the contact area. The diamond point used had a nominal radius of 3.5 mils which was in full contact with the record groove. These records had a thick core (about one quarter inch thick) with a hard plastic material on the surface that held the sound groove. When a transcription is made today with electrical amplification the same stylus force and shape originally used does not have to be used. What are the limitations in the reproduction of the music from the shape and size of the stylus?

The first step to understand is the way that the music groove was cut in the recording blank. The recording at the music studio was made with a soft material and a cutting tool that was driven by the acoustic energy from the musicians. After this original recording was made, the master stamping molds for the actual records were copies from this original recording. When the original recording was made a Patent number 1,024,839 from Edison provides some information about the groove shape. Figure (7) shows some drawings from this patent.

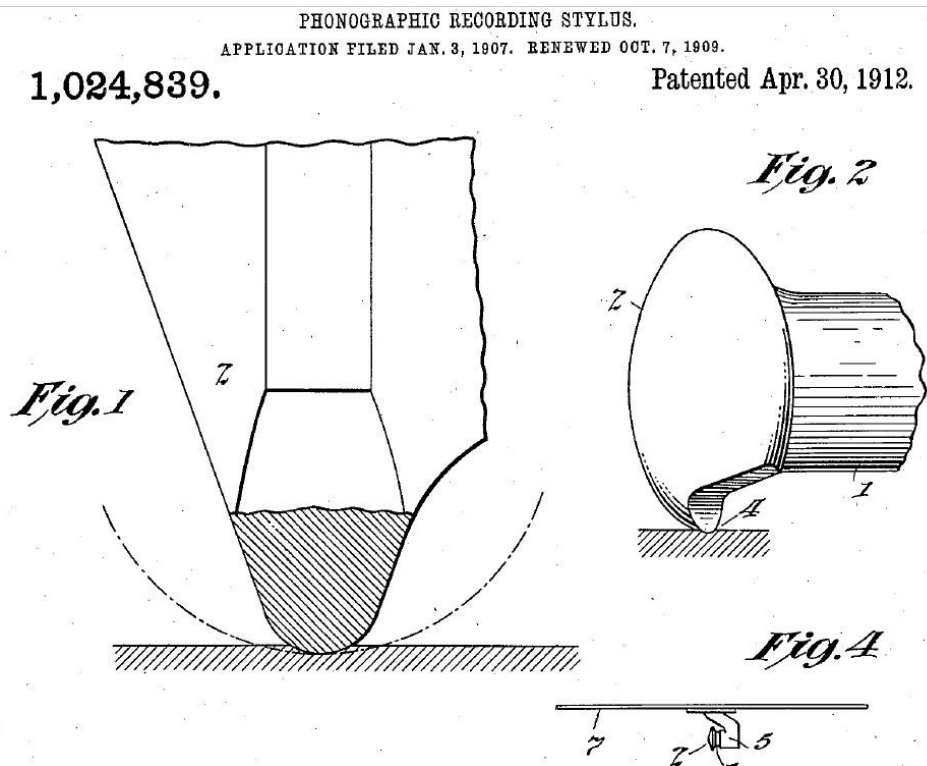


Figure (7) Recording Cutter

In the patent description, Edison refers to the shape in the patent Fig. 2 as that of the head of a pin with a cut made into the surface. From the patent you can see that the groove shape is similar to a chisel with the wide portion cutting up and down with the song as the disk rotates. The important question is *what is the result of using a certain stylus shape as it rides in this record groove cut with the recording cutter?* The results of the Pierce and Hunt Analysis Method can be used to examine the performance of the original diamond disc stylus and a stylus that was found using experimental results to work very well, namely the Reeloc DJ 0.7 OM Black from Ortofon. This stylus from Ortofon is a current DJ style that has a 0.7 mil radius on a spherical polished shape.

Worst Case Calculations for Two Stylus

The *worst-case playback* conditions for the Diamond Disc during a playback will be found at the inside record grooves (close to the center) and for high frequencies of short wavelength. For the calculations, two high frequencies of 4 kHz and 8 kHz and two stylus sizes will be used; the original Diamond Disc 3.75 (max) and a 0.7 mil DJ (Disc Jockey) Spherical Shape designed for “Scratching and Playing” LP records.

First Case: Inside Track (2.38 inches) and 8 kHz sound wave.

$$Vg \text{ (Groove Speed) } \textit{inch/sec} = \frac{(2\pi R) \times \textit{RPM}}{60} = 19.94 \textit{ inch/sec} \textit{ eq (10)}$$

$$a \text{ (peak amplitude) } = 0.87 \textit{ mil} \times (f^0/f) = 0.04 \textit{ mil} \textit{ eq (11)}$$

Where $f_0 = 400 \text{ Hz}$ (Where Max Amplitude Occurs) and $f = 8000 \text{ Hz}$ (note that constant velocity recording was used so that the amplitude will be reduced as the frequency increases per eq (11)).

$$\lambda (\text{Record}) = \frac{Vg}{f(\text{Hz})} = 0.00249 \text{ inch eq (7)}$$

$$Ka = \frac{2\pi a}{\lambda} \text{ and } Kr = \frac{2\pi r}{\lambda} \text{ eq (8)}$$

For 3.75 mil (Original Diamond Disc Stylus), $Kr = 9.46$ and $Ka = 0.10$ which gives from figure (2) a total distortion value $\approx 50\%$.

For 0.7 mil (DJ LP Stylus), $Kr = 1.77$ and $Ka = 0.10$ which gives from figure (2) a total distortion value $\approx 6\%$.

Second Case: Inside Track (2.38 inches) and 4 kHz

Using the same equations as before with value changes $a = 0.00009$ and $\lambda = 0.00498$.

For 3.75 mil, $Kr = 4.73$ and $Ka = 0.11$ which gives from figure (2) a total distortion value $\approx 20\%$.

For 0.7 mil, $Kr = 0.88$ and $Ka = 0.11$ which gives from figure (2) a total distortion value $\approx 5\%$.

Other calculations can be performed on the outside track and for other stylus values, however, important conclusions can now be drawn for the best stylus to transcribe Edison Diamond Disc Records. The use of a current DJ style 0.7 mil spherical shape will perform much better than the original Diamond Disc stylus and should be used. The 3.5 mil Stylus used by Edison was needed, at the time, to support the heavy weight in order to produce a reasonable acoustic output using strictly mechanical means. The fact that a smaller radius for the stylus would provide a better reproduction of the sound was understood by Edison and a patent from 1900 numbered 652,457 describes the elliptical style of stylus that is used today. My understanding of the use of the larger 3.5 mil spherical stylus by Edison was to support the heavy weight needed for practical use of a mechanical sound system.

Because the stylus rides on the bottom of the groove for vertical recording, a smooth and polished tip (as shown in the Edison Drawings) is required. The DJ style seems to have a smooth tip even though this stylus is designed for the LP records where the stylus does not ride on the bottom. Figure (8) was provided by the Ortofon Company for their Reel OM Black DJ Style of stylus. The stylus is a spherical shape and will ride with full contact into the cut groove of a diamond disc since the groove shape is also a spherical shape.

Stylus type - Spherical
Stylus tip radius - R 18 μm

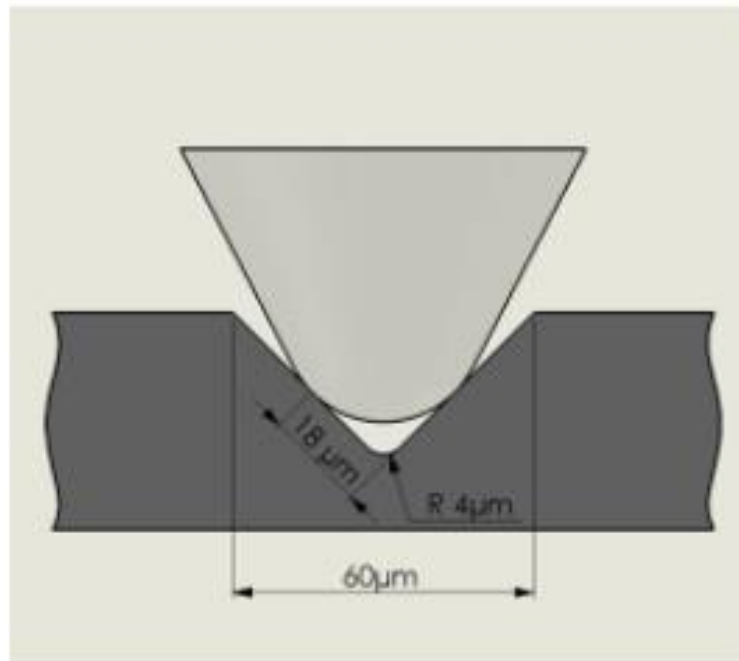


Figure (8) Ortofon Stylus Information

18 micrometers correspond to 0.7 mil and the groove shape in the drawing is for a lateral modulation (4 micrometers is the shape of the groove bottom) application. Ortofon customer service has stated that the bottom and sides of the stylus are polished.

Another very important benefit of using this 0.7 mil tip is that not only are the harmonic distortions reduced from the transcribed music, but the shape of the noise that remains contains high frequency energy which in turn provides the DCart noise

removal algorithms correct information to remove noise events. When similar records using the larger 3.75 mil stylus are processed with the same noise filters settings, more noise events remain verses using the 0.7 mil stylus.

Stylus Selection for 78 RPM Records

Introduction

The study of 78 RPM records with lateral groove motion has produced a large body of information that helps to find an optimum stylus shape. The original stylus used for playback was a soft steel shaped point that was designed to wear *into* the record groove within a couple of record revolutions. Steel particles and years of dirt will often be found in the 78 RPM record grooves even after a good cleaning. Unlike the Edison Diamond Disc records, the stylus *has to ride above the bottom of the groove*. If the stylus was in contact with the bottom of the groove, you would hear a large increase in the noise.

After many record playbacks using the older reproducers, a significant amount of wear in the groove walls will exist which will add to the background noise. Therefore, the stylus selection for the 78 RPM records requires a shape that does not ride on the bottom and a width that is in contact with the smoothest part of the record groove. The best approach is to have a selection of stylus sizes to experimentally find the best transfer since each record has a unique groove situation regarding wear. The section on “Errors in Playback from Stylus Shape for Lateral and Vertical” can provide some general limits to the stylus size to use and the examples will use a spherical shape stylus.

The author has experimentally found that using a 3.5 mil spherical shape stylus for the Nagaoka MP-110 cartridge provides a good transfer for very worn 78 RPM records where the original stylus had a radius of about 2.5 mil. Let’s compare the 3.5 mil stylus and the 2.5 mil version for worst case conditions at the inner radius using 3 kHz and 5 kHz music waves.

First Case: Inside Track (2.0 inches) and 5 kHz sound wave. Using the graph from figure (3) and equation (9), a 2.0 mil radius gives 20 % total harmonic

distortion and a 2.5 mil stylus is $2.5^2/2.0^2 = 1.56$, $1.56 \times 20\%$ or $\approx 31\%$. Using similar calculations, a 3.5 mil stylus gives total harmonic distortion of $3.5^2/2.0^2 = 3.06$, $3.06 \times 20\%$ or $\approx 61\%$.

Second Case: Inside Track (2.0 inches) and 3 kHz sound wave. Using graph from figure (3), a 2.0 mil radius gives 8 % total harmonic distortion and a 2.5 mil stylus $\approx 12\%$. For a 3.5 mil stylus and using figure (3) the total harmonic distortion is $\approx 24\%$.

When comparing these numbers with those of the Diamond Disc recall that a larger amplitude of the sine wave has a *squared effect* on the lateral distortion and that the Diamond Discs used a very low amplitude verses the lateral records. The results from using the graph shows that the best stylus to *minimize* the distortion from the recording \ playback process is to have a small radius that *does not ride in the bottom of the groove*. With the worn condition of many 78 RPM records, a larger radius helps to reduce the noise from the surface with the tradeoff of more harmonic distortion on the high frequencies. For this reason, the best approach is to have a range of stylus to try for the best sound.

Conclusion

The mathematical analysis presented in the book “Sound Recording” by Frayne and Wolfe which built on the original work from Pierce and Hunt provided a useful mathematical relationship between the stylus radius and distortion of the recorded sound groove for both Lateral and Vertical recording. Because information is available from the Edison Music Company regarding actual diamond disc recording values, calculations were shown that a current, DJ style stylus of 0.7 mil radius will provide a low value of distortion for the Diamond Disc Records. This small radius can be used because the stylus rides on the bottom of the groove where the sound is located. This is in sharp contrast to the 78 RPM records that use lateral motion and the same stylus could not be used.

The 78 RPM records cannot have a stylus ride on the bottom of the groove and thus a minimum radius size is needed. Because the record groove had to support

and move a heavy reproducer and shape a soft steel needle, the condition of many of the groove walls have worn sound shapes. Thus, a stylus that rides on a clean part of the groove wall may provide the best result even though high frequency distortion will result.

The original phonograph patent that Thomas Edison wrote claimed vertical and lateral forms of groove motion to record the sound. As time continued from the initial invention, two different music industries developed, one by Edison with the vertical motion and another started by Emile Berliner using the lateral motion. The lateral motion on a flat surface provided a number of early advantages for Berliner by providing a groove that could propel the tonearm by itself and provide a method to reproduce copies by making a metal stamping mold. Edison continued to develop the vertical recording method and needed to add mechanical features to move the tonearm without energy from the sound grooves.

The fact that the sound is placed into the groove using a chisel shape for both vertical and horizontal groove motions and a finite radius to the stylus is used to follow or trace the groove motion means that there will always be some distortion to the signal. The lateral motion with sound on the walls requires a minimum radius to ride higher than the bottom in contrast to the vertical motion that can have a small radius ride on the bottom of the groove.

What this means for us today is since low mass tonearms and electric amplification is available, a much smaller stylus radius can be used for the Edison Diamond Disc records than was originally needed (also the mechanical driven lead screw is not required since the groove can move the low mass tonearm). *The result is that for the Edison Diamond Disc Records a lower distortion to the music is possible verses the 78 RPM records. The 78 RPM records will always require a larger stylus radius than the Diamond Disc Records to ride above the groove bottom.* The resulting distortion to the music has been shown to be significant between these two methods.

Edison Believed that His Recording Method was Better than the Competitions and for Recording sound. Today this belief can be realized and we can use this difference to improve the Sound that was originally heard on the Edison Phonographs.

If you would like to comment on this information, please send me an E-Mail at: hildebrantconsulting@outlook.com