PHYSICAL PROCESSES OF CUTTING GRAMOPHONE RECORDS

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CHAPTER 1

Methods of Sound Recording

Sound recording, i.e. the recording and storing of sound signals aimed at a later reproduction, plays an extraordinarily large part in today's communication systems and has a great importance in the history of civilization. Much technical ingenuity has been and is still exerted to reach the utopian aim: a perfect, true to nature reproduction at an arbitrary point of a "sound image", recorded at another place and time. Today, three different methods are used for the registration of sound; mechanical registration (gramophone), magnetic registration (tape recorders) and optical registration (sound film).

The first system of optical recording and reproducing of sound signals was described in 1901 by Ernst Rühmer (Germany). However, the practical utilisation had to await the appearance of the electron valve, and it was not until 1921 that it became possible to demonstrate the first proper sound film with synchronised sound. The magnetic registration was invented by Valdemar Poulsen, who had his telegraphone patented in 1898. Also in this case, a practical utilisation on a large scale had to await the development of the electron valve and consequently that of the amplifier technique, and not until the end of the twenties did the development gather speed. However, the mechanical registration dates back to the year 1877, when Thomas Edison invented the phonograph, and is thus preceding the magnetic registration by over 20 years. In contrast to the other two methods, an amplifier is not necessary to reproduce the sound phonographic cylinder and gramophone records, as the power available is sufficiently strong to produce a reasonable sound pressure by means of suitable mechanical-acoustic transducers. Naturally, the quality of these recordings is not very good when compared with today's high quality of gramophone records. With the development of magnetic registration, prophecies about the vanishing of gramophone records were made. This will hardly happen as long as mechanical registration, as the only method of those mentioned, offers such easy and low-priced possibilities of producing mass copies of an original recording. On the contrary, the technique in relation to mechanical registration has developed concurrently with the development of magnetic and optical registration, so that quadraphonic records are on the market today, and black/white video records (Teldec system) exist, and colour video records (Philips VCR) with a halfhour playing time are available.

CHAPTER 2

The Historical Development

The first successful attempts of mechanical sound registration probably took place in Paris in the year 1857, when the Englishman Leon Scott designed and patented his Phonautograph. The instrument consisted of a rotary cylinder, on which some soot-coated paper had been wound. A movable rod system with a recording pen which touched the paper of the cylinder was fixed on a diaphragm placed at the bottom of a horn. When the cylinder was rotated and at the same time moved in the direction of the axis line by means of a spindle, the amplitudes of the diaphragm were recorded on the sooty paper. Of course, it was not possible to reproduce the recorded sound signal by means of this instrument.

The first usable instrument also able to reproduce sound was not invented until 20 years later, when Thomas Edison invented his Phonograph. Edison states himself that the invention was made on 13th August, 1877, but the patent application is dated as late as 24th December, 1877, and was approved on 19th February, 1878. By the way, that year (1877) the same idea was submitted to the French Academy "Academie des Sciences" by the French physician Charles Cros. The most important components of Edison's Phonograph are very much like Scott's Phonautograph and it only deviates from this on two points.

Tinfoil was used on the cylinder instead of sooted paper, and the recording pen was placed directly on the diaphragm without the movable rod system. By this method of mounting, the recording pen moved at a perpendicular angle on the foil, so that the vibrations of the diaphragm were recorded in the form of a groove of varying depth. This form of registration is called vertical recording - "hill and dale" recording. The reproduction of the signal was made by placing the same recording pen with diaphragm and horn in the modulated groove, and the cylinder was then rotated, as far as possible at the same speed as during the recording. By this procedure the diaphragm produced vibrations which were more or less in accordance with the registered signal. This process naturally caused very great wear. Various improvements were carried out, and in 1878 Edison was able to introduce a model with wax cylinder and electric motor. However, the preceding year, on 4th May 1877, German-American Emil Berliner applied for a patent on what he called a "Gramophone". Here, the cylinder was replaced by a flat, rotating disc, and the recording pen moved transversely in the groove as in the case of Scott's instrument. This method of registration is called lateral recording. Emil Berliner must therefore be reckoned the proper inventor of the gramophone as it is known today. At this stage, the decisive advantage of Berliner's gramophone in comparison with Edison's phonograph was the ease of mass producing the disc. The cylinders were all original recordings, although in 1903 Edison succeeded in developing a system which enabled him to produce copies of an original cylinder. In comparison, Berliner was very early able to produce a copper or nickel matrix which could be used for the mass production of copies. The main principles of the process are the same as today, and shellac with various fillers, which was the material used for the discs, was in use as late as 1952.

Other inventors, for instance Graham Bell, Volta, Tainter and Eldridge Johnson, also contributed to the development, and before and around the turn of the century a great number of patent and law actions were conducted about the utilisation of these inventions. These strifes resulted in the establishment of various firms, for instance Columbia (Bell-Tainter), Victor (1898, Berliner-Johnson) in the USA, and DGG (1898, Berliner), The Gramophone Company (HMV-EMI) in Europe.

It must be remembered that all recordings and play-backs were purely acoustic-mechanical and that this procedure continued to be used as late as around 1926, when the introduction of the electron valve in connection with electro-mechanical transducers made the so-called "electric" recordings possible. In the intervening time the development was dominated by many small improvements and a better understanding of the theory behind acoustic and mechanical phenomena. In 1919 A. G. Webster propounded the basic theory of acoustic horns, and in 1923 A. E. Kennelly introduced the concepts of acoustic and mechanical impedance. The best acoustic recordings comprised a frequency range of approx. 150 - 4000 Hz, characterized by numerous resonances in the transfer characteristic originating from the recording and reproducing horns etc. The introduction of the amplifier technique, microphones and electromagnetic cutting systems in the course of a few years raised the frequency range attainable to approx. 30 Hz - 10 kHz without any particularly pronounced resonances. The improvement was initially introduced in the recording of the discs, whereas the play-back instrument was often purely mechanical-acoustic. Even in the 1940's portable gramophones were manufactured with spring-driven works and a pick-up consisting of an exchangeable fibre or steel needle, which made a paper or metal diaphragm vibrate via a lever system. Naturally, electro-mechanical pick-ups were developed, especially electro-magnetic and piezo-electric ones, concurrently with the reduction of the necessary tracking force. By acoustic play-back a tracking force as high as 2.5 N was necessary, whereas, at the beginning of the Second World War approx. 0.2 N had been achieved for electro-mechanical pick-ups. After the end of the Second World War mechanical registration was severely pressed by magnetic registration, which could offer a longer playing time, better signal/noise ratio and lower distortion, and the gramophone record companies began to tape the recordings for subsequent cutting of records. The first improvement comprised the replacement of the shellac records with vinyl records, thus reducing the record noise by 10 - 20 dB. Then a variable groove pitch was introduced, so that the groove pitch depended on the modulation. By means of this, the playing time of a normal record could be almost twice as long. Finally, the Long-Playing records with speeds of 33 1/3 and 45 revolutions per minute were launched concurrently with pre-emphasis of the high frequencies at recording. These developments permitted a signal/noise ratio of approx. 55 dB.

Around 1957, only 10 years later, the introduction of the stereo technique became the next important advance. The sorely tried record enthusiast who had in the course of a few years had to acquire a new gramophone with 3 or 4 speeds, a lightweight tone arm with at least two different pick-ups, pre-preamplifiers with play-back characteristics, etc., now experienced a unique phenomenon, namely that internationally the technical details of the stereo system had been agreed on in advance. These details were:

- the application of 45^{o} - 45^{o} flank cutting of the two channels
- placing and phase of right-left channels
- dimensions of the groove
- stylus radii of curvature
- the same pre-emphasis in both channels as in mono

In recent years the development of the recording procedure has been marked by an improved cutting technique and the introduction of "anti"-distortion as a compensation of the geometrical distortion occurring at play-back. Furthermore, noise reducing compressor/expander systems are often used during the actual recording, because tape noise deriving from the original recording often becomes audible, when making the master records. As to the play-back method the development of gramophone turntables with even less wow and hum, better pick-ups with a required tracking power of less than 10 mN, and almost frictionless tone arms with antiskating compensation, parallel motion etc. has taken place parallel with this.

For the time being, the technical problems in connection with 4-channel registration - quadraphonics - are being elaborated on. It seems that the technique to be used will be based on the recording of the two extra channels in the two existing ones by means of a pilot tone technique, as applied in FM-stereo broadcasting. Most major music recordings can be mixed for quadraphonic play-back, even though they are published as stereo records. The technical difficulties are great. The cutting of the masters has to be done at half speed, and as to the play-back equipment few pick-ups are capable of reproducing the necessary frequency range, 20 Hz - 50 kHz.

Even though quadraphonic reproduction is a possible step towards "perfect reproduction", it must be admitted that the difference between quadraphonic and stereophonic reproductions is far less pronounced than the difference between stereophonic and mono reproductions, and the years to come will prove if this technique will gain sufficiently firm ground to induce the large record companies to market quadraphonic records on a large scale. Until now, the records have apparently not been taken on by the consumers, even though a sufficient number of quadraphonic records have been on the market, this despite the high quality which is a result of the care bestowed both on the cutting and on the processing of matrices. In fact, some manufacturers have withdrawn quadraphonic play-back equipment from their range.

CHAPTER 3

Modern Technique

The technique behind a modern record can be roughly divided into three parts, namely the recording of the signal, the cutting and production of the record, and the play-back. The artistic and technical recording problems are beyond the scope of this discussion, and it will just be mentioned that, today, major recordings are often made with a large number of microphones. A number of the microphone signals are mixed in advance, so that the master tape normally comprises at least eight channels. During the recording of the master tape a noise-reducing system with a compressor/expander such as, for instance, the Dolby system is often employed.

During the cutting of the master record, further editing and mixing can take place, so that the resulting signals appear as two-track tape with 2 or 4 channels, stereophonics and quadrophonics respectively. The master consists of an aluminium disc with a thin layer of lacquer (cellulose-nitrate) applied. In this the stereophonic signal is cut as 45° flank cutting by means of an electro-dynamic cutterhead (Neumann, Ortofon or Westrex). A sapphire stylus is normally used for the cutting, and a detailed review of the cutting equipment and the problems in relation to the cutting process is given in chapter 6. The signal registered on the record must meet the international standards concerning amplitude characteristics and groove width and depth. Further, there will be equipment to regulate the width concurrently with the degree of modulation and in the case of some special recordings, also equipment which provides a regulated distortion as compensation for the geometrically conditioned distortion resulting from the replay of the records (Dynagroove, Phase Four, Stereosonic).

From the lacquer original a master negative is now made in an electrolytic bath. The first stage is a chemical cleaning of the lacquer surface and a subsequent sensitisation, enabling a thin layer of metallic silver to adhere to the surface. This layer is applied chemically in the form of a silver-containing solution which liberates metallic silver onto the lacquer surface through reduction. The silver-coated lacquer original is then used as a cathode in a nickel electrolyte bath together with an anode of pure nickel. A DC current of up to 2 kA/m^2 is sent through the electrolyte and in approximately 2 hours a nickel layer of approx. 0.5 mm will be deposited onto the lacquer original.

After this, the master negative is stripped off the lacquer original, by which the lacquer original is normally destroyed. The master is a negative record and could be used directly for the pressing of records. Today, this is seldom done, partly because only a limited number of records can be pressed by means of a master, and partly because this is the only existing copy. The same process is therefore repeated in that, prior to the process, the master negative is subjected to a potassium dichromate bath or to an organic colloid solution, so that a monomolecular film is deposited on the surface. This thin layer is necessary to facilitate the processing of the new copy of the master negative. Often, several mother (metal positives) are produced from the same master. The mother is a positive copy, and this stage of the process is the first one, in which a replay can be made without any risk and the lacquer indirectly checked with regard to its having been cut correctly. Finally, this process is repeated once again, in that a number of stampers (metal negatives) are produced from each mother matrix. These are used in the pressing of the final record. The stamper is normally somewhat thinner than the mother matrix, approx. 0.3 mm, and some companies apply a thin layer of chrome to reduce wear during the pressing. This was essential when the record material was shellac, but today it is considered a questionable measure.

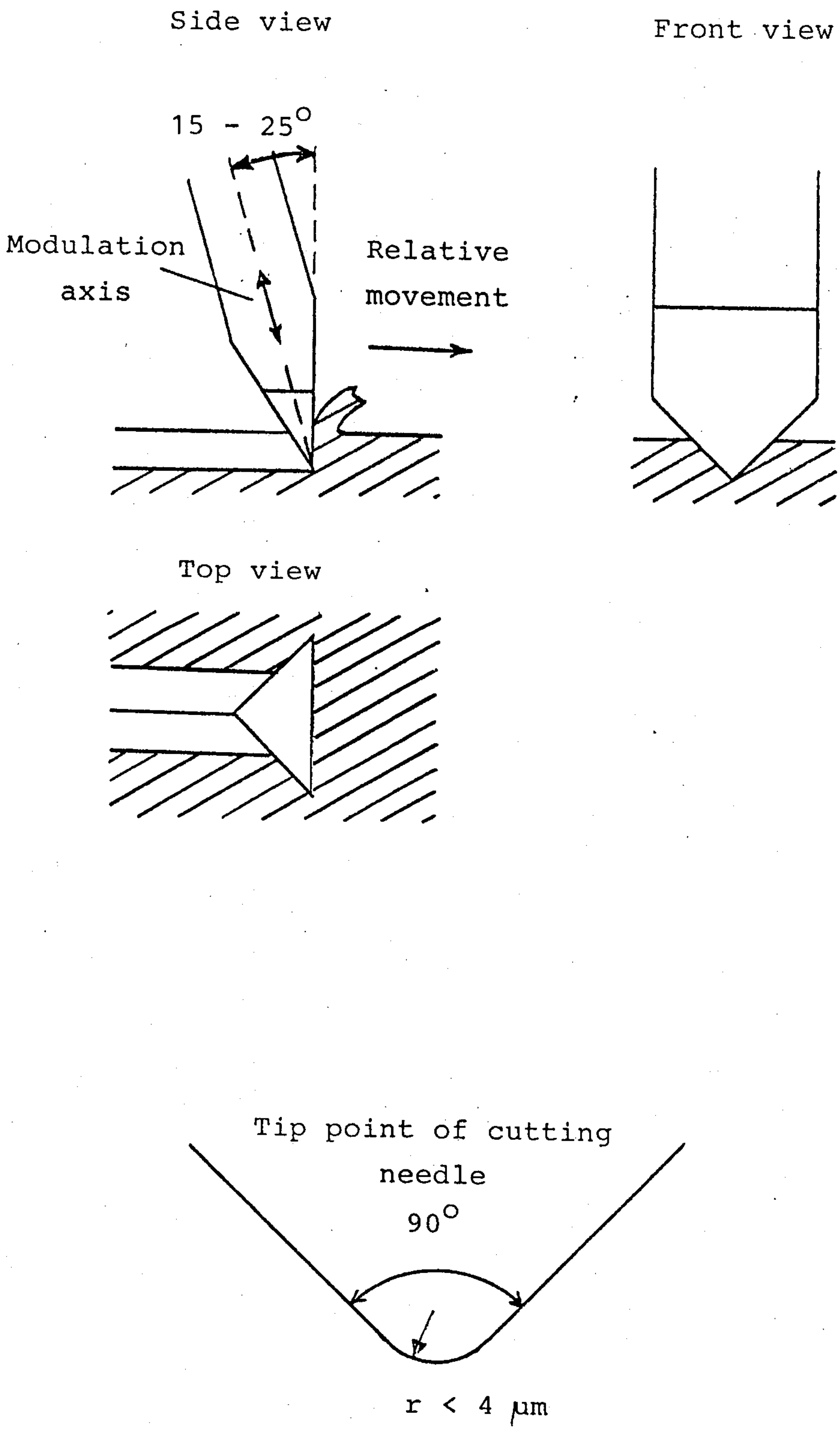
For the production of the records two stampers are used as press matrices. The whole process takes approx. 45 seconds for a 30 cm record. In this time two labels and a disc of record material are placed in the press; the matrices are heated to approx. 160° Centigrade and closed at a pressure of approx. 1500 N/cm^2; the matrices (and the record) are then cooled down to approx. 30° Centigrade; and finally the press is opened and the finished record is removed. Flash trimming is carried out while the press is on the next cycle.

On the average, approx. 100,000 records are pressed by means of a set of matrices, depending on the quality of the finished product which must be maintained.

The records material is selected to suit the conflicting demands for low-surface noise, resistance against wear (within reasonable limits) stability etc., and today it consists of mixed polymers based on vinyl, most often vinyl acetate and vinyl chlorides.

For the cutting process a sapphire stylus is used, shaped as shown in figure 3.1, where the data specified are international standards. Also see IEC Publication 98: Processed Disk Records and Reproducing Equipment.

Figure 3.1


Side view
Front view
15 - 25°
Modulation
axis
Relative
movement
Top view
Tip point of cutting
needle
90°
r < 4 μm

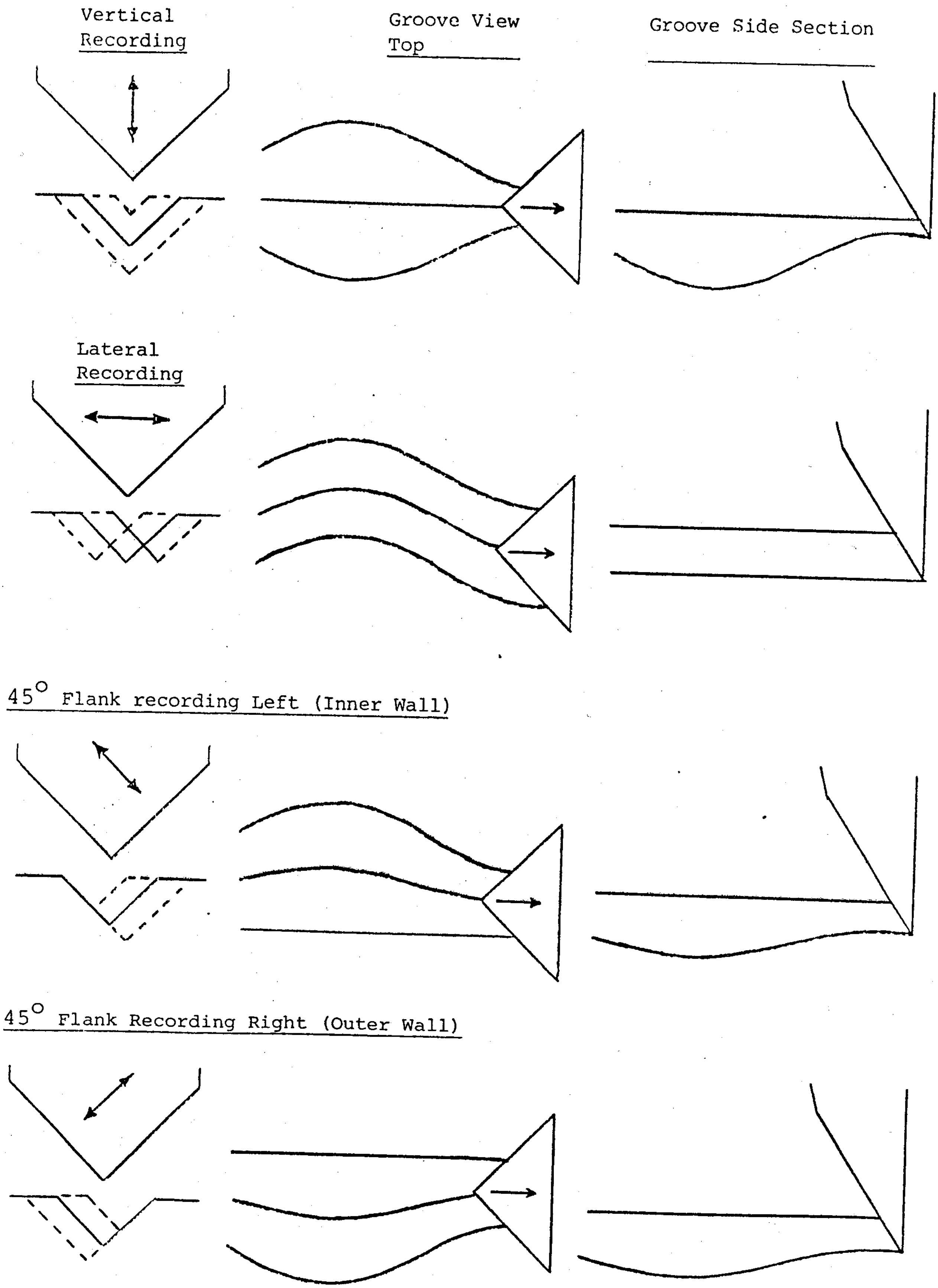

Vertical Recording
Groove View Top
Groove Side Section
Lateral Recording
45° Flank recording Left (Inner Wall)
45° Flank Recording Right (Outer Wall)

Figure 3.2

In chapter 2 it was mentioned that Edison used vertical cutting for his recordings, whereas Berliner used lateral cutting, and that for stereophonic recording 45° flank cutting is used. The three methods of cutting are illustrated in figure 3.2.

From the figures it is seen that 45° flank cutting is produced by a superposition of vertical and lateral cutting. In the case of stereophonic recording the phase levels are such that the sum signal of the two channels is cut laterally, whereas the difference signal is cut vertically. This is owing to the fact that lateral cutting produces less distortion than vertical cutting at playback, and this is compatible with monophonic reproduction.

For play-back a pick-up is used which consists in principle of a fixed shell and a movable stylus, often a diamond or a sapphire, which is placed in the groove cut by the cutting sapphire. The movable stylus is controlled by a vertical force which is great enough to make the stylus remain in the groove during playback of the record. The relative movement between the stylus and the shell is then turned into an electrical signal which, after an appropriate frequency correction, will be a more or less accurate reproduction of the original signal.

In the case of high-quality pick-ups, the mechanical-electrical conversion usually takes place electro-magnetically. At play-back it is important that the tip of the pick-up stylus fits into the groove. In figure 3.3 the correct size is shown. For stereo pick-ups the radius of curvature must be between 13 and 18 µm.

If the stylus is too pointed it will be guided by the bottom of the groove instead of the walls, and dust particles concentrated at the bottom of the groove will cause noise. Correspondingly, a stylus which is too large will be guided by the groove edges. This causes unstable groove tracking and scratches and other damage of the surface will give rise to noise in the reproduction. The optimum conditions are reached when the play-back stylus neither touches the bottom of the groove nor its edges.

In the above it was mentioned that a pick-up consists of a fixed shell and a movable stylus. However, this only implied that the pick-up shell must be kept fixed in relation to the groove. During the cutting of the record the cutting stylus moved constantly along the radius towards the centre of the record and the pick-up moves accordingly. In practice, this is arranged for by placing the pick-up at the end of an easily movable arm (tone arm), which is pivotally mounted. The pick-up will then, unfortunately, make a circular arc instead of a linear movement, which results in an angular error in proportion to the pick-up tracking angle and the groove radius, which causes some distortion in the play-back signal.

For the first 50 years after the appearance of the gramophone record, play-back was, as previously mentioned, made by means of a play-back needle, which, via a rod system, made the diaphragm of a horn vibrate. This had the effect that the sound pressure produced became proportional to the velocity of the pick-up needle. A linear transfer characteristic therefore required that the velocity of the cutting stylus corresponded to the pressed signal. however, this involved too large oscillations of the needle at low frequencies and thus a reduced playing time of the records. Therefore, the cutting studios began to cut the records with constant amplitude oscillations at low frequencies and constant velocity at high frequencies. The shift frequency varied between 200 and 800 Hz. Eventually, as the technique was improved, the nuisance of stylus noise at high frequencies became more apparent, and it became clear that the S/N ratio could be improved by emphasising the high notes at the recording and attenuate them correspondingly at play-back. With the introduction of the stereo technique a recording characteristic as shown in figure 3.4, (where the velocity of the cutting stylus is shown as a function of the frequency), was agreed upon internationally.

If using a true to velocity play-back pick-up, for instance such as a pick-up based on an electro-magnetic conversion, the signal from the pick-up must therefore be adjusted with the reciprocal curve. The reason why the recording characteristic is always stated in reference to the velocity of the cutting stylus is historical. If, however, the characteristic is stated in reference to the amplitude, as shown in figure 3.5, it appears that the recording characteristic can more advantageously be expressed in terms of constant amplitude of the cutting stylus, but in such a way that the high frequencies are attenuated and the low frequencies are emphasised about 6 dB, 1 kHz being the reference. The shape of the curve is chosen by historical observations of the amplitude distribution of music and the dynamic conditions at the cutting of the records as well as the S/N ratio required.

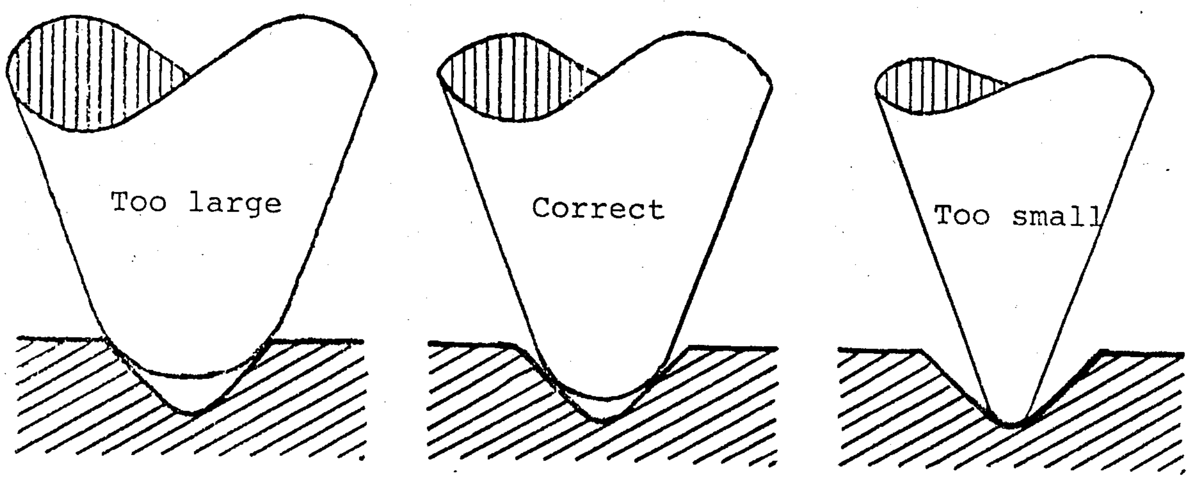


Figure 3.3 Size of Pick-up Stylus in Proportion to Dimensions of Groove

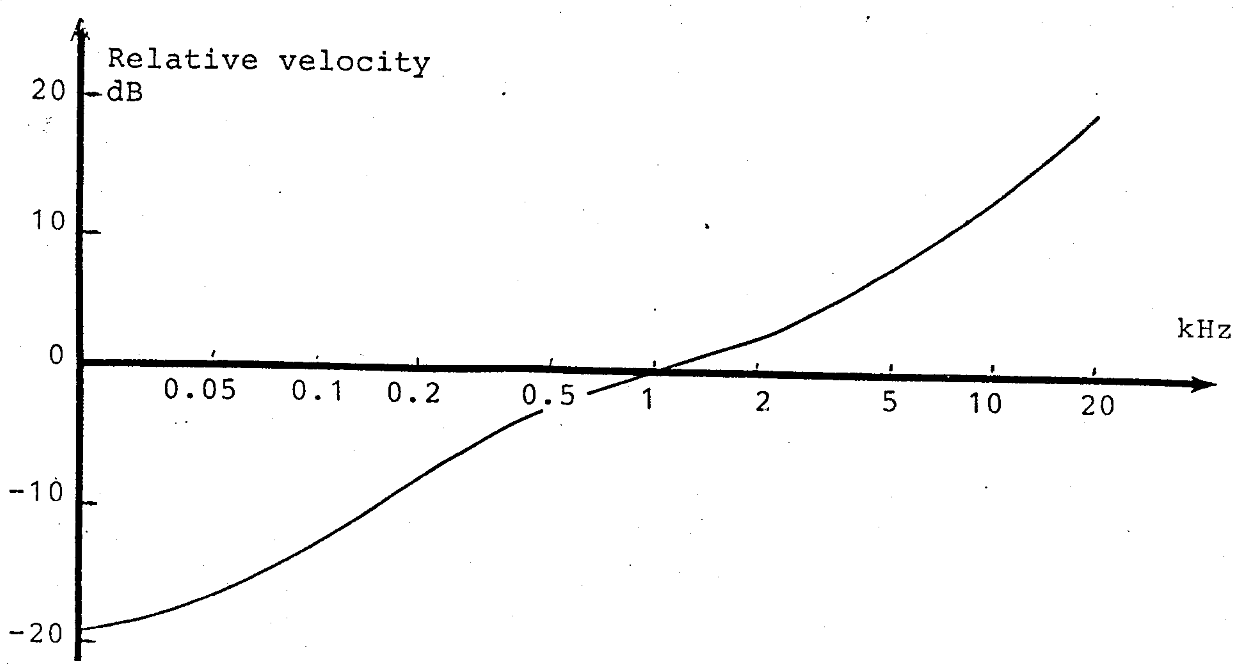


Figure 3.4 Recording Characteristic

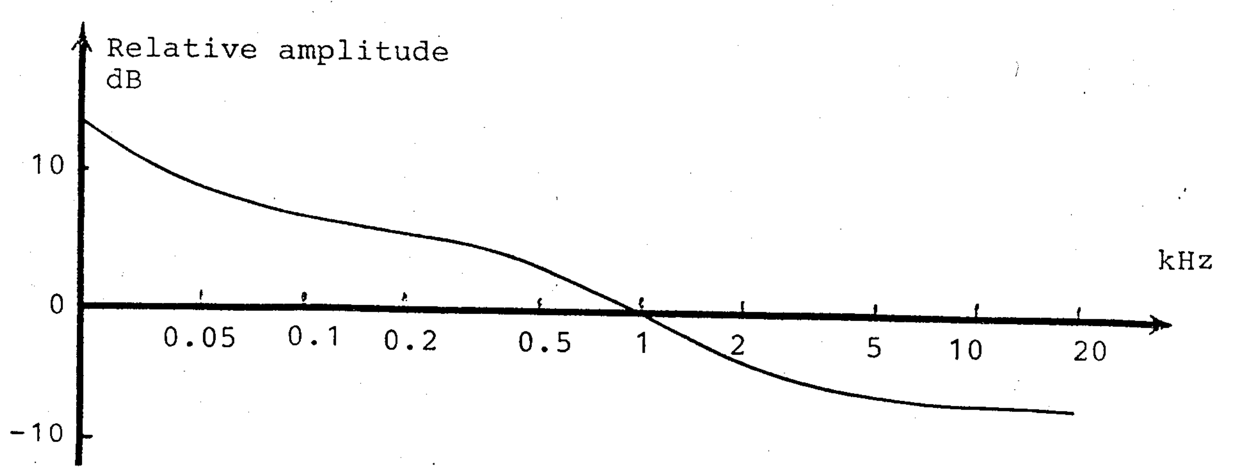


Figure 3.5 Recording Characteristic

CHAPTER 4

General Comments on the Play-Back of Gramophone Records

As mentioned in the last chapter, a pick-up stylus is placed in the groove for play-back of gramophone records, and endeavours are made to have the stylus strictly track the amplitudes of the groove, thus providing an accurate reproduction of the recorded signal. On an ordinary stereo record, the maximum amplitudes of the groove will be about 50 µm at the loudest passages and about 50 nm at the quitest ones. In order to track these amplitudes, the stylus must, in the audio frequency range, oscillate at speeds which may peak as high as 30 cm/s and in the extremes, 80 cm/s. This has the effect that, at high frequencies, the stylus is exposed to an acceleration which may be more than 1000 g (10^4 m/s^2). For ordinary stereo records the frequency range is about 20 Hz - 20 kHz (up to 50 kHz for quadrophonic records). Thus, great demands are made on the capability of the pick-up to track the groove, and it must be expected that the groove is elastically deformed during the play-back. To this can be added that, owing to its size, the stylus is not able to make the same movement as the cutting sapphire. These tracking errors or tracking distortions are partly conditioned by the geometric proportions.

The various forms of tracking errors and the consequent distortion of the reproduced signal can be described systematically in the following way:

Initially, it is assumed that the hemispherical stylus tip of the pick-up, see Figure 3.3., is constantly touching both groove walls, and that no deformation of the groove occurs. Under these circumstances a geometrically conditioned tracking error will occur because of the shape and size of the stylus tip point (i.e. deviation from the cutting sapphire chisel shape). The influence of the tracking error depends on the mode of cutting (vertical - lateral). Also some lateral and vertical tracking angle errors will arise. This is owing to the fact that the pick-up stylus and its suspension in the lateral and vertical plane respectively may deviate from the plane at which the cutting stylus moved. The distortion caused by the tracking errors is also dependent on the mode of cutting.

Common to the tracking errors mentioned above is the fact that they are all conditioned by purely geometrical proportions, thereby enabling calculation. Among other things, this is the reason why it is possible partly to correct the distortion during the cutting of the records, if a sufficient amount of variable parameters have been built into the cutting system.

Then, it is assumed that the stylus tip point is steadily in contact with both groove walls, but that an elastic deformation of the groove walls occurs. This deformation depends on the elastic properties of the record material and on the stress, i.e. the degree of modulation, the stylus force etc. The resultant distortion can therefore only be calculated approximately.

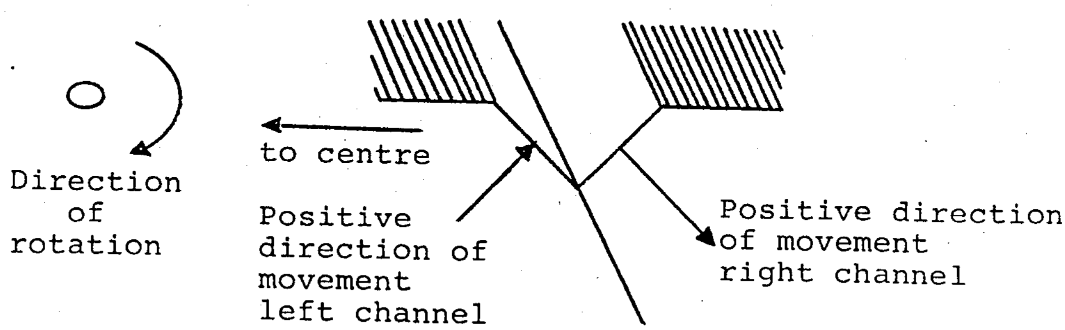
Finally, it is assumed that the stylus tip point loses contact with one or both groove walls, or the cone-shaped side of the stylus is in contact with the groove. This can of course only occur under extreme conditions and can normally be avoided.

The problems mentioned above all concern the movement of the stylus tip point in proportion to the registered signal, and the errors consequently arising are all classified as tracking errors. The next problem which appears is to what extent the electro-motive force output expresses the movement of the stylus tip point. The greatest problem here is mechanical resonances in the suspension of the stylus etc. These resonances cause the mechanical impedance of the pick-up, as seen from the surface in touch with the groove walls, to take on large values at certain frequencies, which again result in large deformations of the groove, and which also have the effect that the pick-up may not remain in touch with the groove at these frequencies. From this can be seen that some of the tracking errors are partly dependent on the mechanical impedance of the pick-up, and that it is the pick-up designer's greatest task to develop a pick-up with the lowest possible mechanical impedance. This will both result in low distortion and a low degree of wear both of records as well as the pick-up stylus.

Channel Separation in Stereo Records

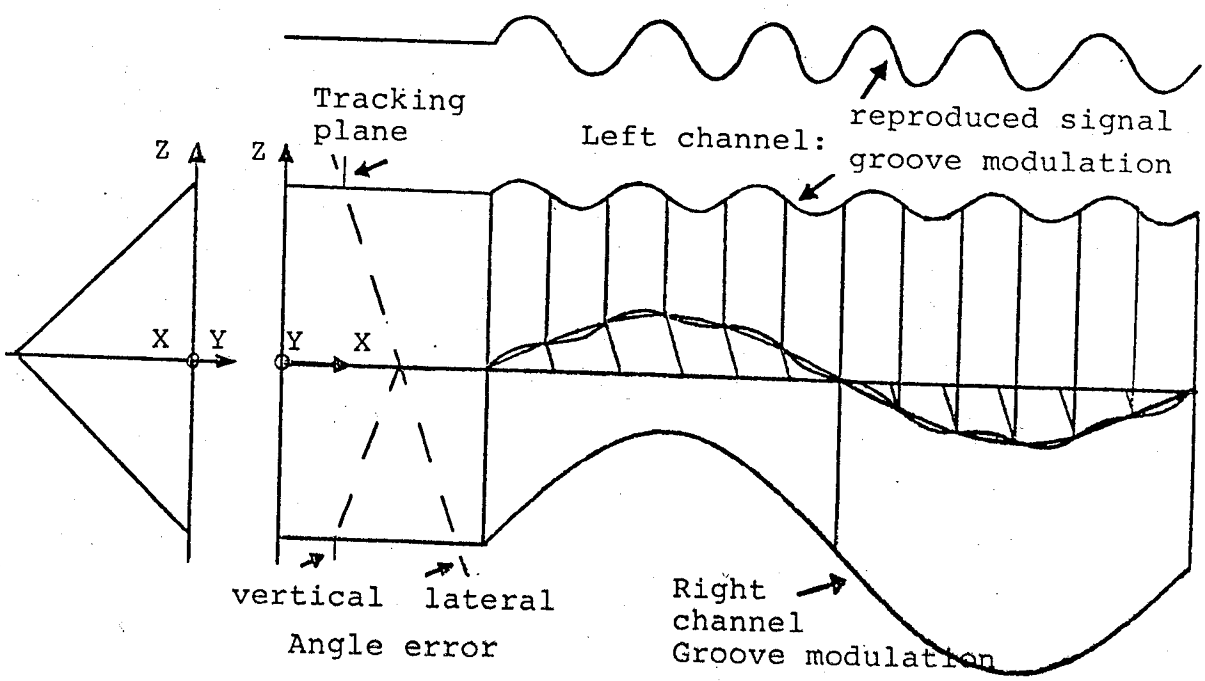
When recording two channels at the same time (stereophonics) each signal is cut on one of the two groove walls, see Figure 5.1. Both groove walls form an angle of 45° to the surface. The play-back pick-up contains two electro-mechanical systems placed perpendicularly to each other, so that each of them separately reproduces the movement of the stylus in one of the two groove planes. Now, if it is assumed that there has been no tracking angle error at the recording, and that the geometric proportions in the cutterhead and the pick-up are perfect, the movement of the stylus and consequently also the electrical signal of the two terminals will each depend separately on the modulation of the specific groove wall. Therefore, the conditions at the two groove walls can be looked upon independently of each other.

Figure 5.1



If it is now assumed that during the play-back there is a vertical and a lateral tracking angle error, a cross modulation will arise between the two signals. This is illustrated in Figure 5.2, where a strong low frequency is recorded in one channel and a weaker high frequency is recorded in the other. The pick-up stylus will now follow the outlined tracking plane, and as appears from Figure 5.2 the high frequency signal will be frequency modulated together with the low-frequency one.

Figure 5.2



By crosstalk between two channels, A and B, is understood the relationship between the undesired signal at the output of channel B (A), deriving from a signal in channel A (B), and the desired signal at the output of channel A (B), i.e. the crosstalk relations in terms of dB are determined by

$$20 \log \frac{U_B(S_A)}{U_A(S_A)} \quad \text{and} \quad 20 \log \frac{U_A(S_B)}{U_B(S_B)} \text{ dB} \qquad (5\text{-}1)$$

where S_A (S_B) is the signal sent to channel A (B), and U_A and U_B are the corresponding output voltage of the two channels. The size of the two relations given under (5-1) is not unequivocally determined, as a change of the amplification in one channel will change the crosstalk proportion. Therefore, it is often more relevant to work on the channel separation concept. Channel separation between two channels, A and B, is understood to be the proportion between the undesired signal in channel A (B) deriving from a signal in channel B (A) and the desired signal in channel A (B), when a signal of the same amplitude is sent to channel A (B), i.e. the channel separation in terms of dB is determined by

$$20 \log \frac{U_A(S_B)}{U_A(S_A)} \quad \text{and} \quad 20 \log \frac{U_B(S_A)}{U_B(S_B)} \quad \text{dB} \qquad (5\text{-}2)$$

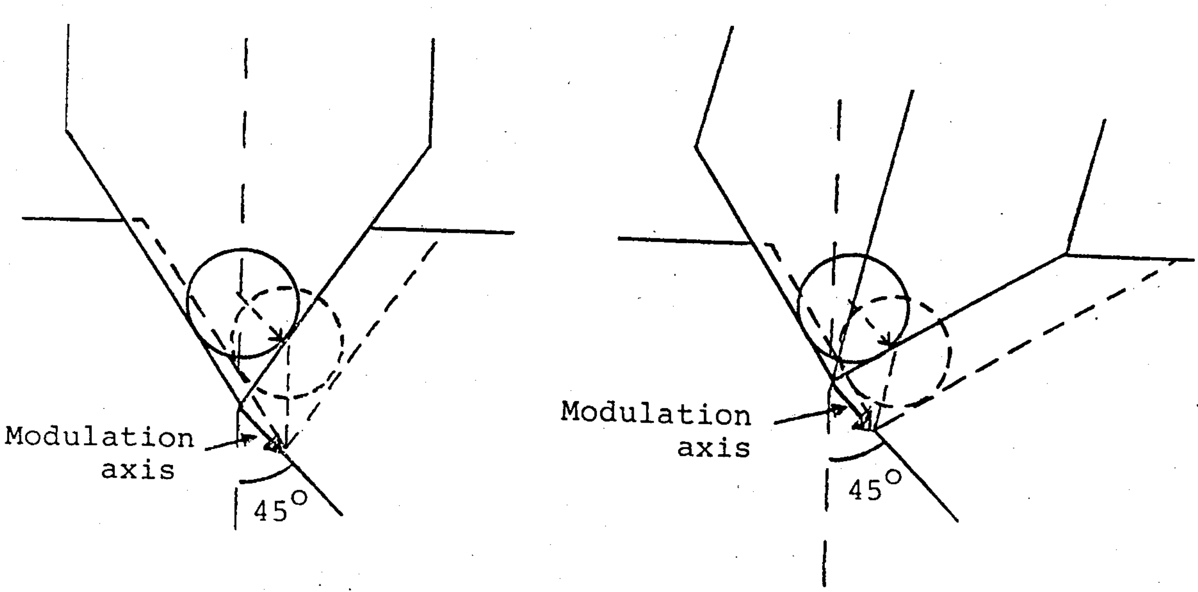
As to measurements, the same signal is transferred to the two channels alternately, enabling the level difference between the corresponding signals at each output to be determined. In the theoretical discussion in this chapter it is an assumption that the amplification of the two channels is equal. The most important factors influencing crosstalk are

a) the effective cutting axes
b) the effective vertical cutting angle
c) the effective pick-up axes

and their interrelations.

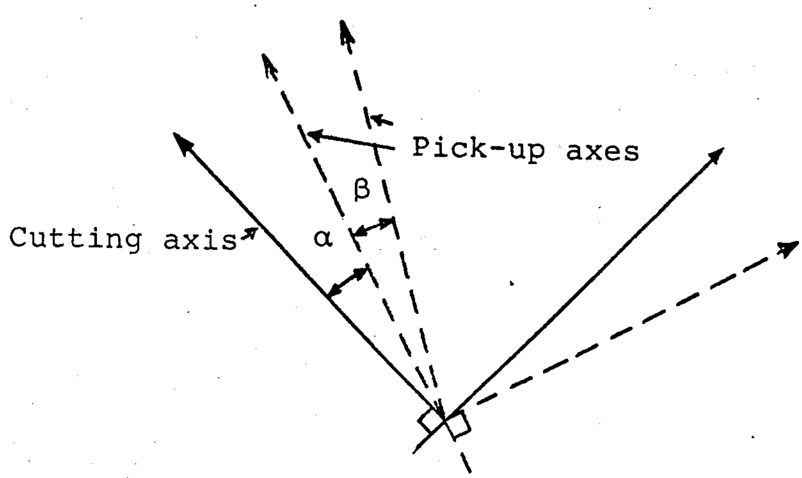
As already mentioned in the introduction of this chapter, there will be no crosstalk between the channels provided that the geometrical proportions at the cutting and play-back of the record are correct, i.e. the effective cutting and pick-up axes are identical. In the case of purely geometrical considerations it can be seen (Figure 5.3) that an opening angle of the cutting stylus other than 90°, or an obliquely mounted cutting stylus, will not cause any crosstalk either, if the effective modulation axes are identical, during both cutting and play-back.

Figure 5.3



Nor will an obliquely mounted pick-up stylus result in crosstalk in itself, as long as it is the ball-shaped part of the tip point which is in contact with the groove walls. If the effective cutting axes and pick-up axes are not identical, there will, on the other hand, occur crosstalk between the channels. If it is assumed that no vertical or lateral tracking angle errors exist at the play-back stage, crosstalk will be determined as shown in Figure 5.4.

Figure 5.4

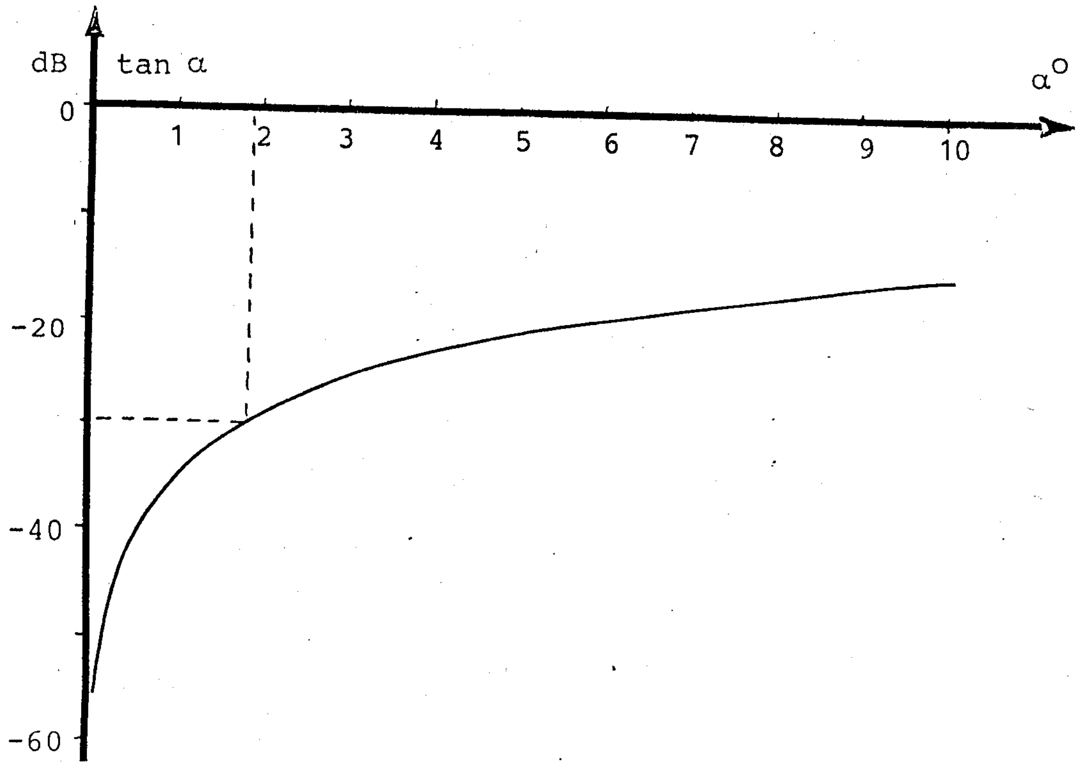


If the angles between the axes of the cutterhead and the axes of the pick-up are equally large, for instance 90°, but, for instance, the pick-up system is obliquely mounted, the two sets of axes deviate with an angle of α . It immediately appears from Figure 5.4 that the channel separation is determined by

$$20 \log \frac{\sin \alpha}{\cos \alpha} = 20 \log \tan \alpha \quad \text{dB} \qquad (5\text{-}3)$$

This quantity is shown in Figure 5.5, from which it appears that a channel separation of not less than 30 dB requires an angle error to be no more than 1.8°.

Figure 5.5
Channel separation



If the angle between the pick-up axes deviates further from 90° by the quantity β, either positive or negative, it can be seen from Figure 5.4 that the channel separation between the two channels differs and assumes the values

$$20 \log \tan (\alpha + \beta) \quad \text{and} \quad 20 \log \tan \alpha \quad \text{dB} \qquad (5\text{-}4)$$

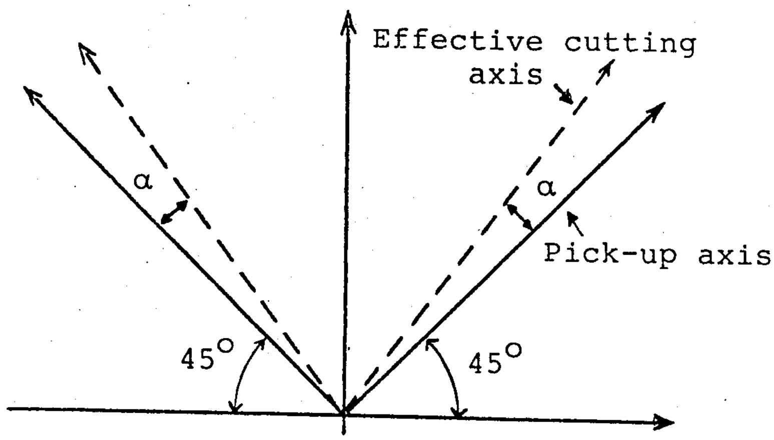
On the other hand, the crosstalk relation between the channels is determined by

$$20 \log \frac{\sin (\alpha + \beta)}{\cos \alpha} \quad \text{and} \quad 20 \log \frac{\sin \alpha}{\cos (\alpha + \beta)} \quad \text{dB} \qquad (5\text{-}5)$$

If it is assumed that it is the cutting axis that causes a deviation of the angle from 90°, it is found that the expressions for channel separation (5-4) and crosstalk ratio must be interchanged.

If it is now provided that both cutting axes and pick-up axes are at right angles to each other, but that, in the vertical plane, the two channels form an angle θ_v with each other, crosstalk between the channels will arise. (Figure 5-6).

Figure 5.6



The effective cutting axes, determined in the plane of the pick-up axes, will mutually form an angle, which is slightly smaller than 90°, when Θ_v is positive, as shown in Figure 5.6, and somewhat larger than 90° when Θ_v is negative. The angle α is determined by

$$\tan(45 - \alpha) = \cos\Theta_v$$

the channel separation thus being

$$20 \log \tan\alpha = 20 \log \frac{1 - \cos\Theta_v}{1 + \cos\Theta_v} \text{ dB} \qquad (5\text{-}6)$$

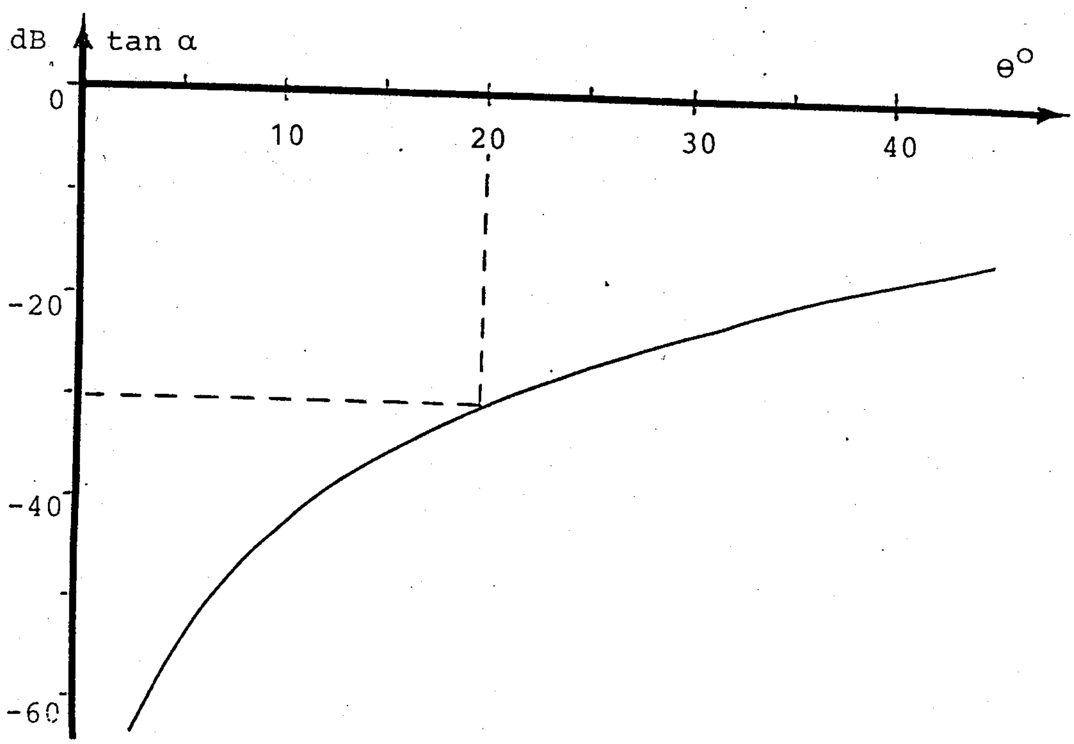
This quantity is shown in Figure 5-7, from which it appears that a channel separation of not less than 30 dB requires the vertical angle error to be 20° at a maximum. This means that a vertical angle error does not have any great influence on the channel separation. A similar expression can be found for lateral angle errors.

From the above considerations it can be seen that, on the basis of measurements of the channel separation, one cannot immediately decide if the error is caused by the cutterhead or the pick-up.

However, an observation of the phase levels may be a further help. The crosstalk signal will either be in the same phase or be in phase opposition to the required signal, which can also be seen for instance from Figure 5.4 or 5.6. If several errors are present at the same time, it appears from 5-4 and 5-5 that the errors may neutralize each other in one channel alone. Generally, optimum results can be obtained when the channel separation and the phase of the crosstalk signal are identical for both channels.

Figure 5.7

Channel separation



CHAPTER 6

Recording of Gramophone Records

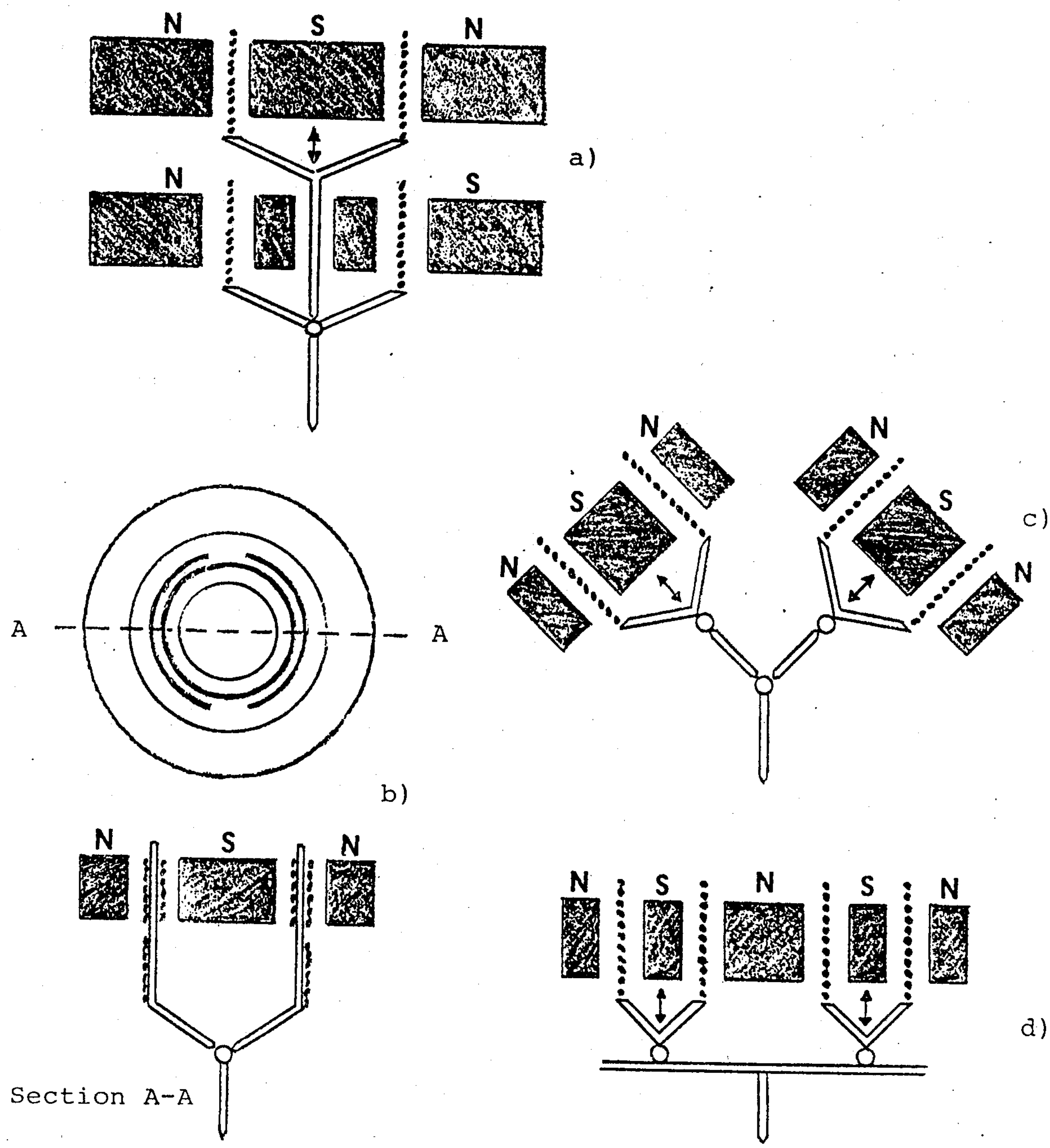
Chapter 3 was largely an exposition of how the cutting of master records and the succeeding processing of the matrices is done. In this chapter the electro-mechanical problems in connection with the cutterhead and the elastic problems arising during the cutting of the lacquer original will be discussed.

In fact, the cutting of the lacquer original is a machining of the surface, and, as previously mentioned, a sapphire or ruby stylus is used as the "cutting tool". The exact design of this is expounded in chapter 7. Further, chapter 8 mentions the maximum limits of the cutting velocity as well as the various systems required to obtain variable groove pitch and cutting depth.

A cutterhead is an electro-mechanical transducer which produces the movements of the cutting stylus during the cutting of the lacquer original in accordance with the externally applied electrical signal. The stylus must be able to move in two planes perpendicular to each other (stereo and quadraphonics) without any interaction between the two movements. These requirements have had the consequence that, today, only electro-dynamic (moving-coil) cutterheads are produced, whereas, previously electro-magnetic and piezo-electric cutterheads (monophonic) were available. Examples of the principles of such electro-dynamic two-channel cutterheads are shown in figure 6.1 a-d. The two early systems, which are no longer in production, are based on the M-S principle and are in fact a lateral and a vertical cutterhead built together as an integral unit (figure 6.1 a). The upper system alone provides for the vertical movements and can therefore cut the S-signal (the difference signal), whereas the coil of the lower system will rotate on its suspension pivot and thereby perform a lateral movement corresponding to the M-signal (sum-signal). The lateral movement can move independently of the vertical one, whereas the vertical system, when an S-signal is present, must also activate the whole lateral system. This limits the level of the cut S-signal in proportion to the M-signal, and this is the main reason why the system is no longer used. In figure 6.1 b, the lateral system has a special design which only requires a single magnet system. However, the movable mass of the vertical system is not the same as the equivalent movable mass (moment of inertia) of the lateral system, and as it is at the same time difficult to avoid an intercoupling of the coils, the use of this principle has also ceased.

6.2

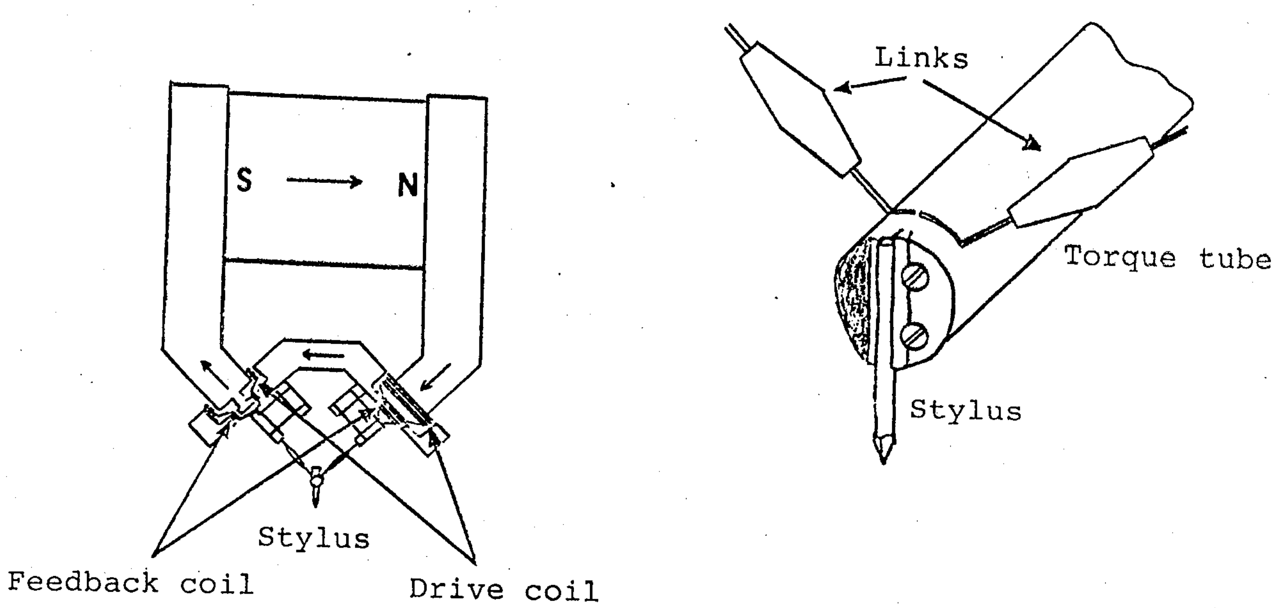
Figure 6.1



Various Principles of
Dynamic Cutterheads

The principle shown in figure 6.1 c is used by the firms of Westrex and Neumann. The two systems shown can work independently of each other and are in fact identical. The coil support springs are designed so that the coils can only move parallel to the end pole pieces. As an example of this figure 6.2 shows the principle of the Westrex-3D cutterhead. The mechanical linkage between the two pairs of feedback and drive coils is relatively large, however, which makes it difficult to control resonances in the system.

Figure 6.2

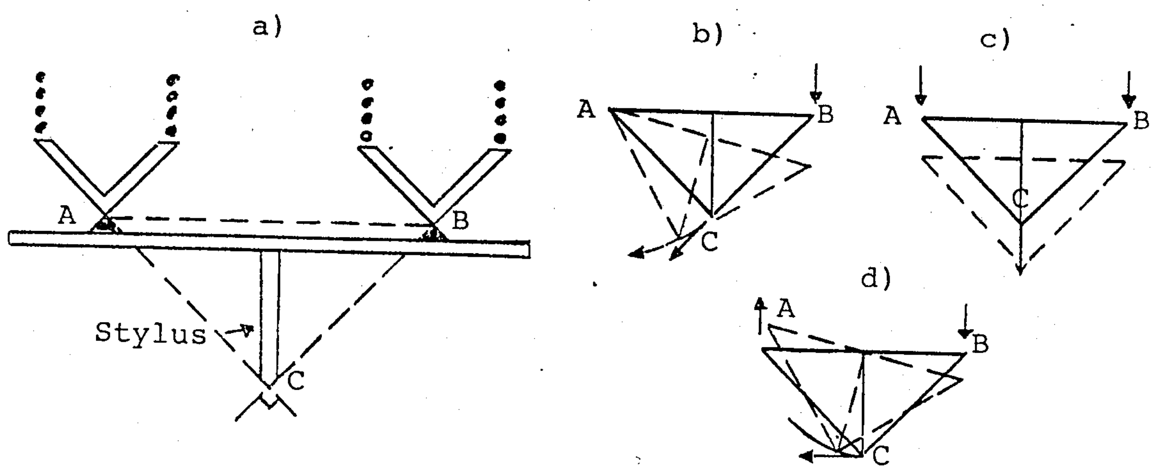


WESTREX-3D Cutterhead

For accuracy it is necessary that the cutting stylus and holder are absolutely rigid and can only make translatory movements, as it is the intersection point of the two axes of rotation in the system that provides for the movement desired, and the top point of the stylus is located at a distance from this. In practice breakdown resonances do appear in the links, even though these wires are supported by a layer of magnesium, and torque resonances appear in the stylus holder. The main resonance of the freely movable system is at about 1 kHz.

The principle as shown in figure 6.1 d is used by Ortofon, and since it is not self-evident that the system can record stereophonic signals, the principle will be expounded in more detail. The cutting stylus is mounted in a bridge connected at both ends to the two moving-coil systems. The moving coils are suspended to allow for translatory movements in the direction of axis, whereas the connection to the bridge provides for rotary movements. The geometry of the moving system is shown in figure 6.3.

Figure 6.3

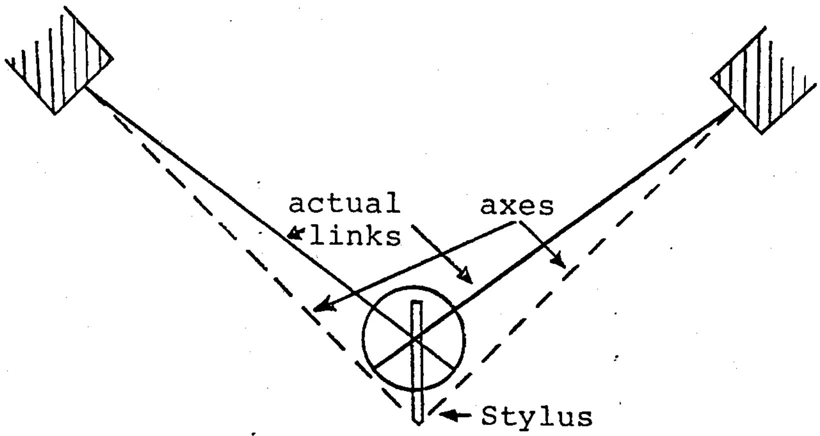


Principle of Ortofon DSS cutterhead

A 45^{o} - 45^{o} side-wall recording can be obtained if the cutting stylus tip forms the right angle in an equal-sided, right-angled triangle, ACB, the distance between the attachment of the bridge to the moving coils being the hypotenuse. From figure 6.3 b can be seen that if one coil is constrained while the other moves, the tip point will describe a circular arc whose tangent forms an angle of 45^{o} to the bridge. As the oscillations are negligible compared to the dimensions of the bridge, the movement of the stylus can be considered rectilinear. From figures 6.3 c and 6.3 d respectively can similarly be seen that two identical signals in the moving coils, in phase and out of phase respectively, will result in vertical and lateral recording. This means that, during stereophonic recording, the signal from the two channels can be led to the respective moving coils, but the phase of one channel must be inverted, which causes the sum signal to be recorded as lateral cutting to be compatible with monophonic reproducing equipment. This also applies to the system figure 6.1 c.

It can be seen that the movement of the stylus in this system also describes an arc.

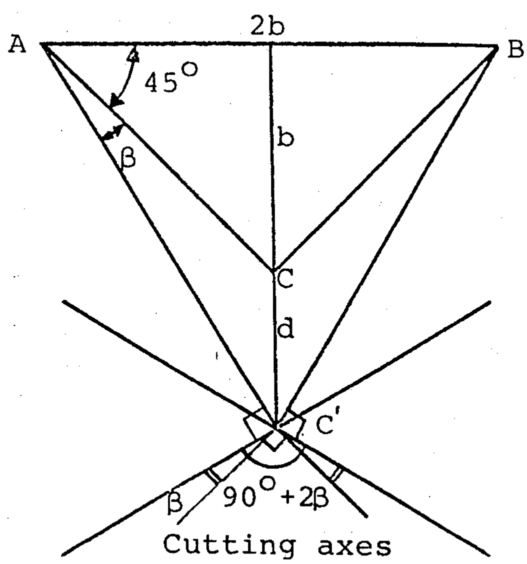
Figure 6.4



Principle from Figure 6.1 c; Illustrates Minimum Crosstalk

In figure 6.4 it is shown how the axes of rotation are placed in relation to the position of the stylus, and it is indicated how the moving coil systems are connected to the suspension of the stylus.

Figure 6.5



Calculation of Crosstalk Caused by Wrong Sapphire Length

It is important that the tip point of the cutting stylus is placed at the correct distance from the systems, because the cutting axes will not otherwise be perpendicular to each other.

Any error can readily be seen from figure 6.5, where the stylus is too long. The channel separation will then be determined by:

$$20 \log (\tan \beta) \quad (\text{dB}) \tag{6-1}$$

where tan β is derived from:

$$\tan (45 + \beta) = \frac{\tan 45 + \tan \beta}{\tan 45 - \tan \beta} = \frac{1 + \tan \beta}{1 - \tan \beta} = \frac{b+d}{d}$$

hence

$$\tan \beta = \frac{d}{2b + d}$$

The channel separation will then be

$$20 \log \frac{d}{2b + d} \ \text{dB} \tag{6-2}$$

A separation of more than 30 dB thus requires that $b > 15.3\ d$, which means that, for a typical value, $b = 4$ mm, it is found that $d < 0.26$ mm. Similarly, an obliquely centred stylus will cause crosstalk between the channels.

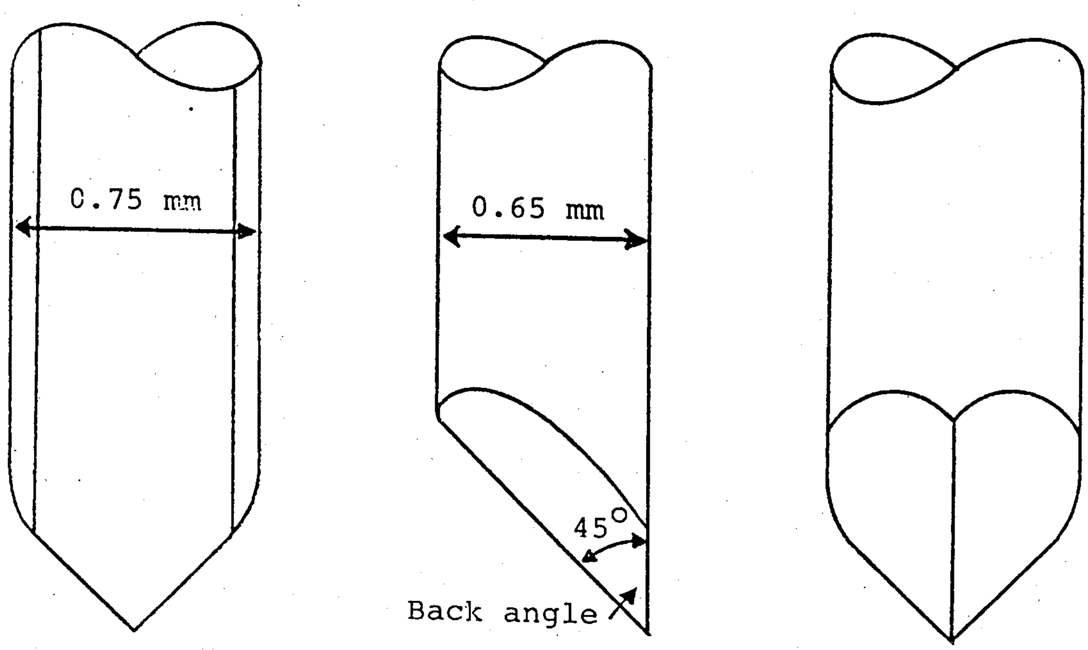
Crosstalk also arises if the vertical axis differs during cutting and replay. This possibility of error was looked into in chapter 4 and illustrated in figure 4.3.

CHAPTER 7

The Geometry of the Cutting Stylus

Technologically, the cutting of the lacquer original is a machining process, whereby the material to be machined passes a cutting tool, the cutting stylus, at a certain velocity v, and the cutting stylus performs microscopic swinging movements around a fulcrum. The cutting stylus is of corundum (Al_2O_3) with a hexagonal crystalline structure. These crystals can be produced synthetically as rubies, sapphires etc., but the blue sapphire has proved the best one for cutting stylii, as this material can be produced without grains and impurities and can therefore be ground into a shape with very clean, sharp edges. The principle shape of the cutting stylus is shown in figure 7.1, in which a cylindrical sapphire is ground to enable the cutting of a V-shaped groove in the lacquer original.

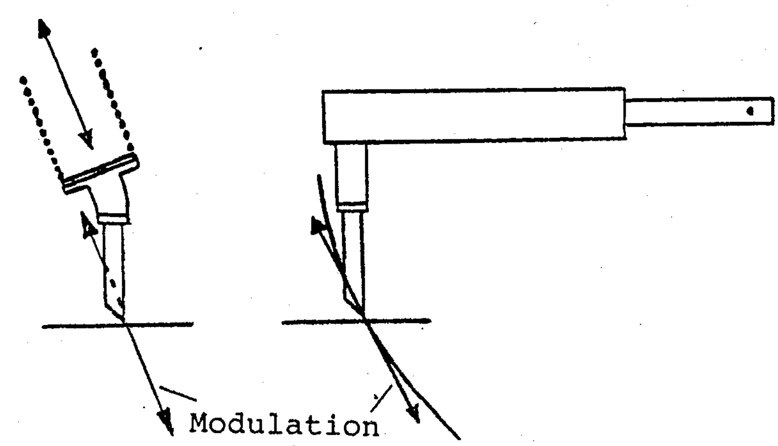
Figure 7.1



Design of Cutting Sapphire for Ortofon Cutterhead.

During cutting, the cutting face of the stylus must be perpendicular to the lacquer. At the same time the modulation of the cutting must result in a 20° vertical tracking angle. The collet must therefore be obliquely mounted to meet the modulation axes, as shown in figure 7.2. In practice, how-

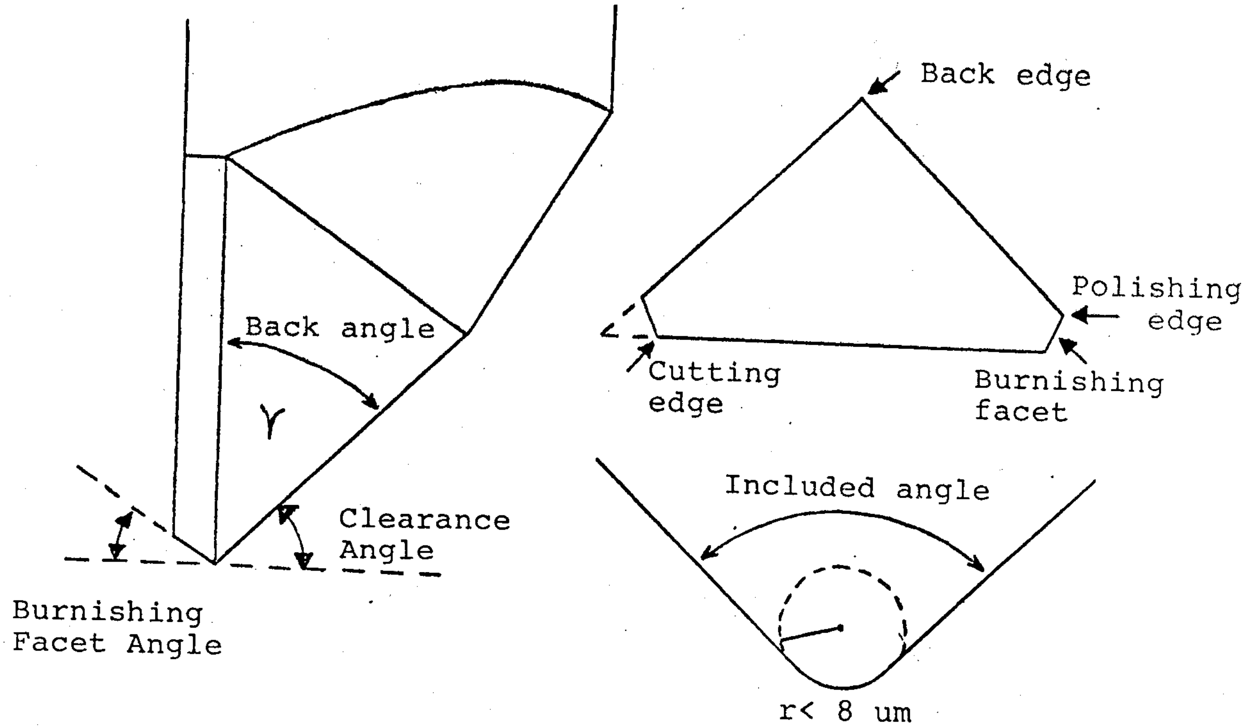
Figure 7.2



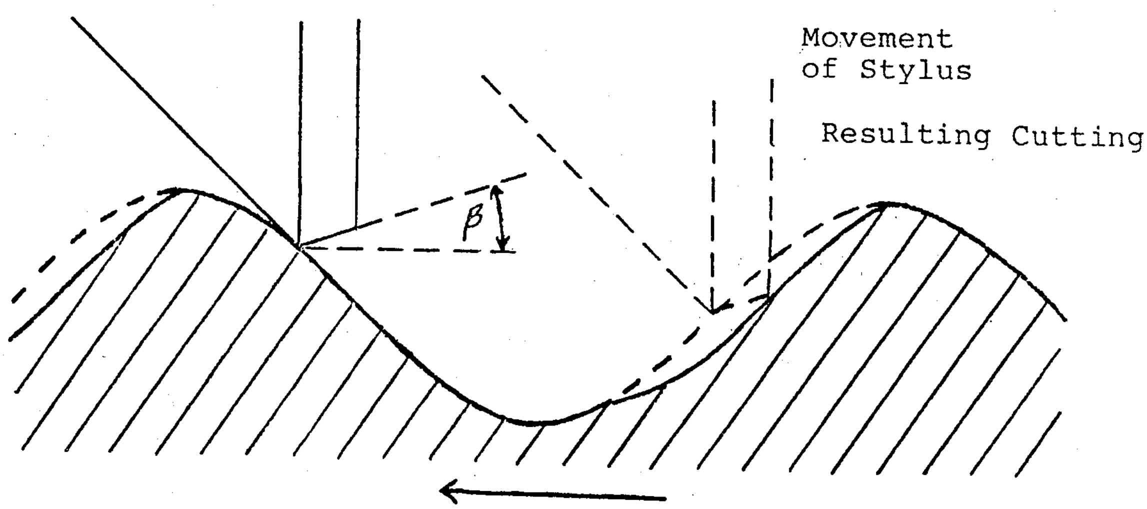
ever, the cutting stylus will not be exactly as illustrated in figure 7.1, because the groove would not be sufficiently smooth, and noise will therefore appear in the recorded signal. In order to achieve a smoother groove, the cutting stylus is provided with an additional facet, which polishes (burnishes) the groove, cf. figure 7.3 showing the cutting stylus with the various designations of the facets, angles, etc. The included angle is approx. 90°, but this value is not critical. Large included angles result in a deeper tracking of the pick-up stylus in the groove, by which scratches in the surface will become less annoying. At the same time it becomes easier to separate the galvanic-produced matrices. On the other hand, small included angles give smoother swarf at the cutting and hence less noise. Finally, it must be remembered that an included angle of 90° of the cutting stylus will cause the effective groove angle to become larger in that the cutting stylus moves in a plane which forms a certain angle (approx. 20°) with the vertical plane.

The radius of the cutting stylus tip point must at the most be half the size of the pick-up stylus radius to ensure noiseless reproduction. Therefore, a value less than 8 µm is prescribed, and in practice values around 3 - 4 µm are used. Technically, the value ought to be as small as possible, but the durability of the cutting stylus is heavily diminished at low values. The

Figure 7.3



size of the polished facets is equally important to the finished result. For geometrical reasons the facets should not exist, because at strong modulations they deform the signal cut, which can readily be seen from figure 7.4, whereas, at normal modulations, they only press the lacquer material which has not

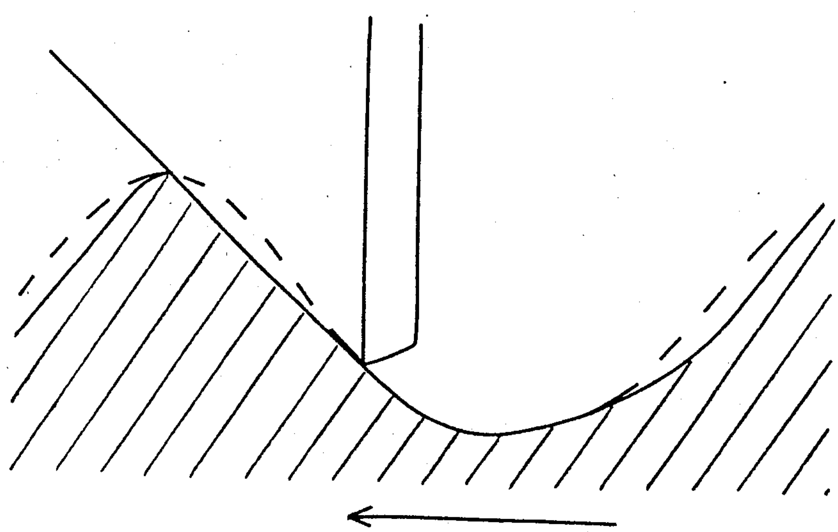


Groove Deformed by Burnishing Facet

been removed out to the sides and are thus smoothing out roughness from the cutting process. In practice, the advantages of these facets have proved to be greater than the drawbacks, and the facets are approx. 3 - 4 μm for normal stereophonic cutting and 1 - 1.5 μm for quadrophonic cutting. The angle β is approx. 20^{o}.

The last important factor in relation to the cutting stylus is the back angle (resistance angle). For geometric reasons, this also ought to be zero, but the size of the angle determines the mechanical strength of the stylus. The size of the angle also determines the maximum modulation velocity, as the back of the stylus may deform the signal already cut, cf. figures 7.4 and 7.5. The back angle γ is normally 45^{o}, but for quadrophonic cutting a cutting stylus with an angle of $\gamma = 35^{o}$ is used.

Figure 7.5



The Signal Cut Deformed by the Stylus Back Edge