

Vertical Tracking Angle— A Source of IM Distortion

An analysis of the distortion resulting from the discrepancy between the vertical angle at which the record is cut and the vertical angle of the playback stylus. A proposal is made to standardize these angles.

E. R. MADSEN*

PROBLEMS CONCERNING THE reproduction of stereo records have been considered from the viewpoint of reproduction quality previously. M. S. Corrington and T. Murakami of R.C.A. Victor have analyzed the relationships and found that when using the 45/45 system and a 90-deg. groove angle with the ideal playback cartridge, there is no cross-modulation between the two channels. Intermodulation and harmonic distortion are identical for the two channels and are the same as they appear with a normal hill-and-dale record. If the records are cut with a groove angle of 90 deg. between the two channels, and the two axes of the cartridge are at right angles to the movement of the two respective grooves, there will be no cross-talk from one channel to the other. These are ideal conditions. In the following discussion it will be shown how unevenly and confusingly the various makes of

records are cut—a confusion that not only makes for listening variations of the many records, but also gives quite a few headaches to the playback cartridge designer. These problems could be avoided if agreement could be reached on standardization of disc cutting procedures.

Perhaps the historical background is partly responsible for the wide disagreement on methods. It should be remembered that the first experiments with stereophonic phonograph records began about 1930. At first the vertical-lateral system was used, although even at that time mention was made of the 45/45 system now in use. In a way the two systems are identical, since by suitable phasing of the two information channels, it is possible to change from one system to the other, making it practical to cut with either system using the same cutting apparatus. Correspondingly, a pickup constructed for the one system can, by means of suitable phasing, be used to play the other system.

* Chief Audio Engineer, Bang and Olufsen, Denmark.

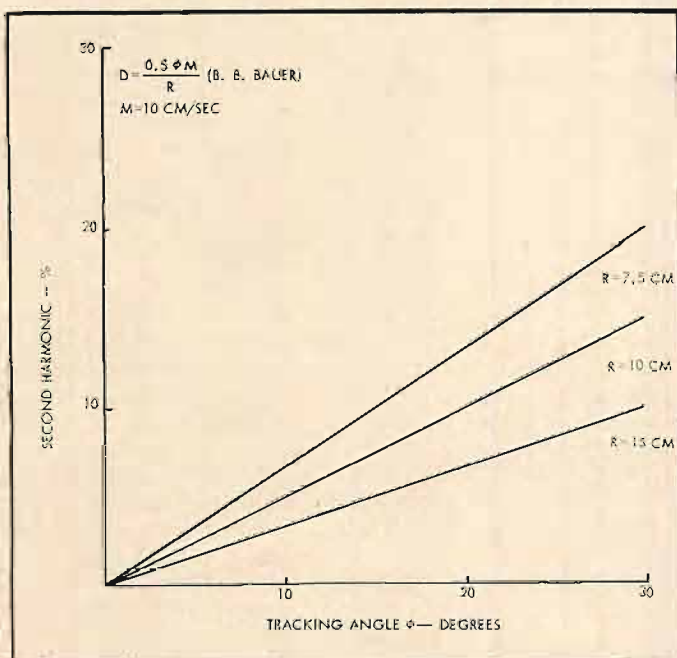


Fig. 1. The percent of second harmonic as a function of tracking angle and modulation.

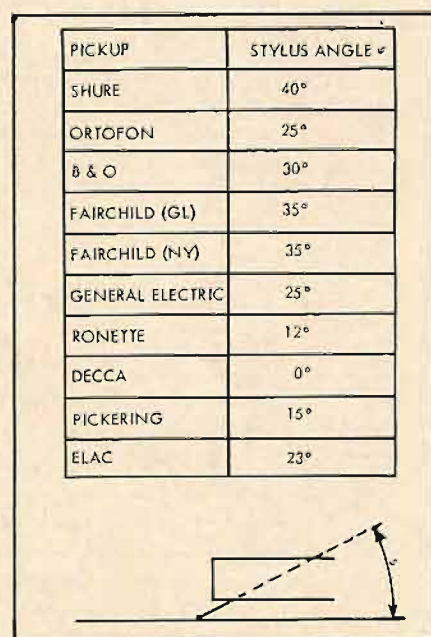


Fig. 2. Stylus cantilever angle in a variety of cartridges.

This is not the place to discuss the advantages and disadvantages of one system versus the other, but merely to point out that from the historic development, equipment to record and play back stereo records has been largely derived from the vertical-lateral system. It is this existing equipment which impedes work in creating agreement on standards for the 45/45 system which has been accepted.

Stereo phonograph records only became a reality after the development of the Westrex stereo disc system. Stereo records were first made available to the general public in the United States. The fundamental work on the method of constructing stereo playback cartridges therefore came from C. C. Davis' and J. G. Frayne's description of the Westrex system which was publicized in the spring of 1958. In June, 1958, the al-

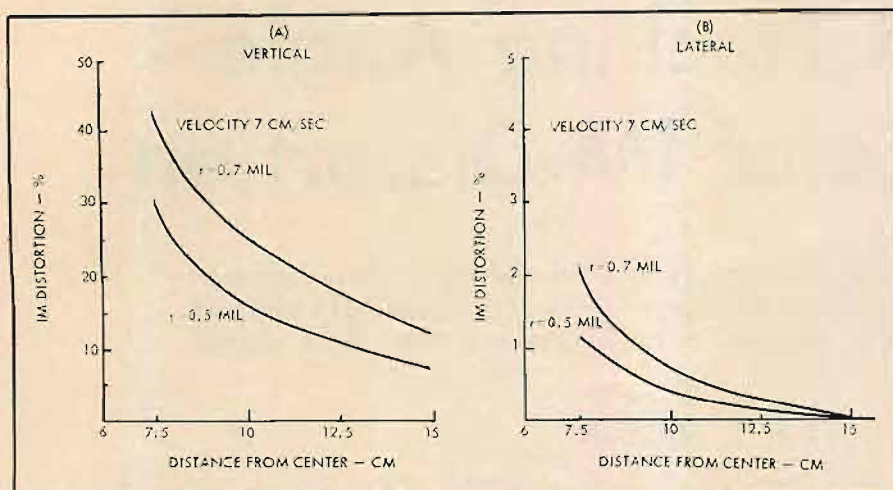


Fig. 3. Vertical and lateral IM distortion as a function of the distance from the center of the record and stylus-tip radius.

ready mentioned work of Corrington and Murakami in the *R.C.A. Review*, which weighed the merits of the vertical-lateral and the 45/45 system in regard to distortion, favored the latter system.

Since it is impractical to place the

in reality a variation of a considerable angle from the vertical. In the Westrex system, this angle is set at 23 deg.

Calculations have been made of the harmonic distortion which appears when playing a laterally-modulated phono-

When: φ is the variation in tracking angle in degrees
 M is the modulation amplitude in cm/sec
 R is the radius from the groove to the center of the record in cm.

It can be seen that the distortion is independent of the frequency, and only dependent on the modulation and the distance of the stylus from the center of the record, and of course the tracking angle. The formula is computed for a laterally cut groove with a record rotation speed of $33\frac{1}{3}$ revolutions per minute. Figure 1 shows the tracking angle distortion at different places on the record, with a modulation of 10 cm/sec. In a well-constructed tone arm the variation from the correct tracking angle can be held to within 1 deg., plus or minus; in other words, in a good playback cartridge it can be demanded that the second harmonic be less than 1 per cent with normal modulation.

Bauer's formula can also be used for a vertically cut groove but additional information is required, because the harmonic distortion will depend here to a great extent on the frequency and on the radius of the stylus. It should be noted that the harmonic distortion is always greater for a vertically cut groove than for a lateral cut. At 1000 cps it will be about 5-6 times as great. Here I refer to the basic work of J. A. Pierce and F. V. Hunt in the *Journal of the Acoustic Society of America*, 1938.

Of the same magnitude, indeed sometimes worse, is the distortion obtained when playing with the wrong vertical tracking angle.

Distortion measurements have been made on a number of test records, using a B & O stereo pickup. The results are shown in Table I. The average figures for the right and left channel, recalculated for all records to $33\frac{1}{3}$ rpm and with a modulation of 10 cm/sec, and a distance from groove to record center of 10 cm (about the middle of the record) are shown at the far right. On the basis of these measurements, and after comparison with the curves of Fig. 1, the presumed cutting angles for the vertical cutting are indicated.

Harmonic distortion resulting from an incorrect tracking angle consists mostly of second harmonic. The third harmonic is about 12-15 db down from the second.

We can see from Table I that the lateral distortion is unimportant in comparison with the vertical so that we may assume the tracking angle is correct for it. Vertical modulation shows considerable second harmonic distortion, however, dependent on the make of record. In order to compare the various records, recalculation (average value for both channels at $33\frac{1}{3}$ rpm) has been made in

TEST RECORD	FREQUENCY (CPS)	GROOVE RADIUS (CM)	MOD. (CM/SEC)	SECOND HARMONIC (%)				AVG. VALUE R = 10 CM. M = 10 CM/SEC LEFT + RIGHT 2	CALC. CUTTING ANGLE
				LAT.	VERT.	LEFT	RIGHT		
OR 1006	400	8-10	6.3	2	10	6	8	11	8°
OR 1005	400	8-10	6.3	0.9	7.5	5	6	5.7	13°
E-V 695 D (78)	1000	7-9	6	0.55		1	1	2.1	24°
WESTREX 1 A/B (78)	1000	14.5	5.5	0.8	1.4	1	0.9	5.5	19°
DECCA 99102 A/B	1030	10	1			1.6	1.6	16	0°
DG 99102 A/B	1030	14.5	3			6	6	11	8°
RCA 12/5/71	1030	14.5	3.8			0.8	0.8	3	24°

TABLE I. Distortion measurements of a number of test records.

axis of revolution of the stylus cantilever exactly at the surface of the record, a vertical tracking distortion will arise unless there is a very close agreement between the angle used by the cutting head and by the pickup. What is normally referred to as the vertical movement of the tip of the cutting stylus is

graph record with the incorrect tracking angle. According to B. B. Bauer ("Tracking angle in phonograph pickups," *Electronics*, March, 1945) the formula for the second harmonic when using the wrong tracking angle is

$$D = \frac{0.5\varphi M}{R}$$

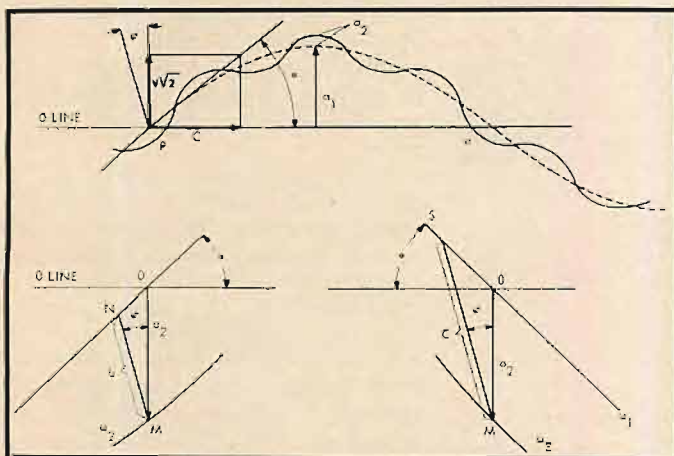


Fig. 4. A double-modulated groove and the result of incorrect tracking angle.

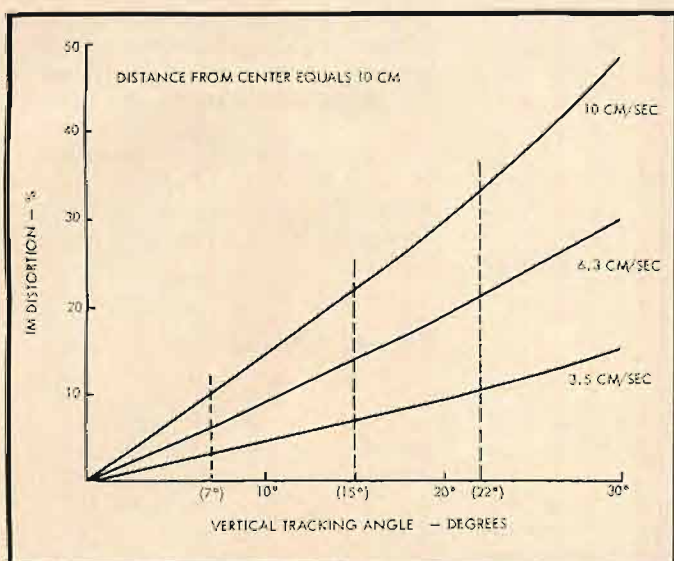


Fig. 5. IM distortion as a function of vertical tracking angle and recording level.

PICKUP	B	D	F	O	R	S	
LATERAL	4	15	18	4.5	7	5	ORTOFON 1006 A (8°)
VERTICAL	37	7.5	55	40	20	40	
LEFT	25	10	40	30	10	30	
RIGHT	28	10	30	25	12	25	
LATERAL	5	16	24	5	15	8	ORTOFON 1005 A (13°)
VERTICAL	60	8	65	60	40	75	
LEFT	40	12	55	35	50	50	
RIGHT	50	12	60	40	30	50	
LATERAL	10	15	23	10	10	10	ORTOFON 1005 A (13°)
VERTICAL	25	12	60	40	12	45	
LEFT	15	10	40	15	12	25	
RIGHT	20	10	50	25	12	30	
LATERAL	10	16	23	10	10	10	ORTOFON 1005 A (13°)
VERTICAL	40	25	72	40	20	70	
LEFT	20	15	26	25	20	50	
RIGHT	25	15	25	35	30	50	

TABLE II. Intermodulation of a number of cartridges.

the next-to-last column. The difference is obvious between records from Decca, at the one extreme, with RCA, Westrex, and Electro-Voice at the other.

From the viewpoint of the playback cartridge designer, a fairly large vertical cutting angle would be preferable, as it is necessary to allow space for the moving elements, whose center of rotation must lie above the record surface.

The angle of the stylus cantilever to the record surface of several pickups has been determined by measurement and is shown in Fig. 2. It is evident that there is as much difference here as with the various cutting angles for the records—the result of a lack of standards for recording.

As mentioned earlier, the most important harmonic distortion is second harmonic due to the incorrect vertical tracking angle. In the case of groove modulation with two tones, an intermodulation product appears as well. As far as is known no previous theoretical calculation has been made of the size of this product as a function of the tracking angle. An attempt to make such a calculation will therefore be made here.

If you first assume a correct vertical tracking angle, there is considerably more intermodulation distortion in playing a vertically modulated groove than is the case with a laterally modulated groove. Corrington and Murakami give the following formula:

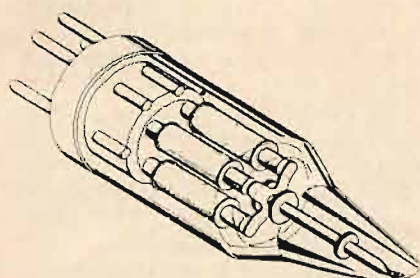


Fig. 6. Principle of the B & O cartridge.

$$IM = \frac{800\pi u_1 r}{v^2}$$

where: u_1 is the lowest frequency recorded amplitude in ips

r is the radius of the stylus in thousandths of an inch

v is the record speed in ips.

With a $33\frac{1}{3}$ -rpm record,

$$v = \frac{2R33\frac{1}{3}}{60}$$

R is the radius from the stylus tip to the center of the record.

In Fig. 3 the intermodulation distortion is shown respectively vertically and laterally with a stylus tip radius of 0.5 mil and 0.7 mil and a recording speed of 7 cm/sec at various distances from the center of the record.

As can be seen, the intermodulation is about 10 times as large in the vertical channel as in the lateral. Intermodulation in the lateral cutting appears as modulation of the even harmonics, and in vertical cutting it appears as modulation of

the odd harmonics. It looks severe, and it is not improved by an incorrect vertical tracking angle.

In Fig. 4 a vertical double-modulated groove is diagrammed. We imagine the groove to be traced by an ideal stylus, and try to investigate what will happen due to a wrong vertical tracking angle. This groove is considered to be cut with a vertical cutting angle of 0 deg.

The angle for zero transmission of the lowest frequency is α , the amplitude of the low frequency is a_1 , and for the high frequency a_2 . The minimum and maximum values which will be obtained for a_2 will be found at the points of zero transmission, which are p and q . The difference between these values of a_2 at points p and q , divided by the average amplitude of a_2 , multiplied by 100 will equal the percentage of intermodulation of the odd harmonics.

In Fig. 4 the areas about points p and q are shown magnified. a_2 is the amplitude for the high frequency, as it would be with the correct delineation ($\varphi=0$), b is the size at point p with delineation under the angle φ , and c the size at point q with delineation under angle φ .

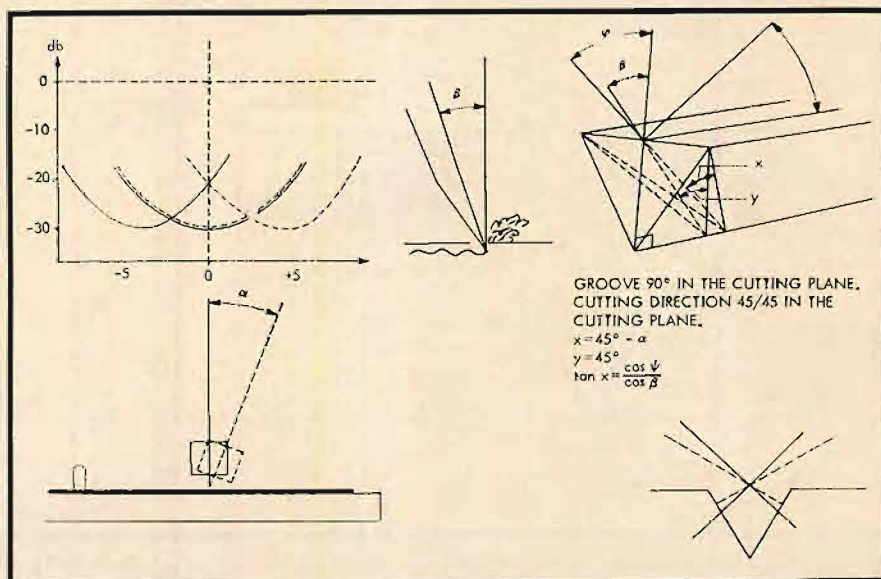


Fig. 7. Some geometrical relationships in the stereo groove.

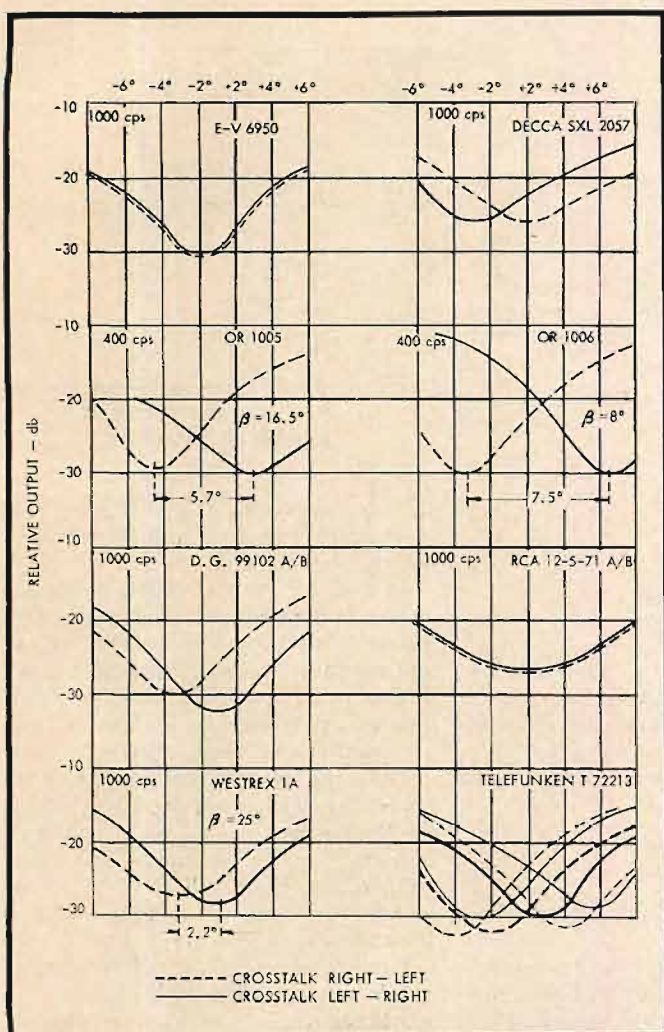


Fig. 8. Crosstalk curves for a variety of test records.

The percentage of intermodulation is expressed as:

$$IM = \frac{c - b}{a_2 Z} 100\% \quad \text{Eq. (1)}$$

Z is a factor that determines the aver-

age amplitude of a_2 with delineation under the angle φ .

For small values of φ however,

$$Z \cong \frac{1}{\cos \varphi}. \quad \text{For larger angles the correct}$$

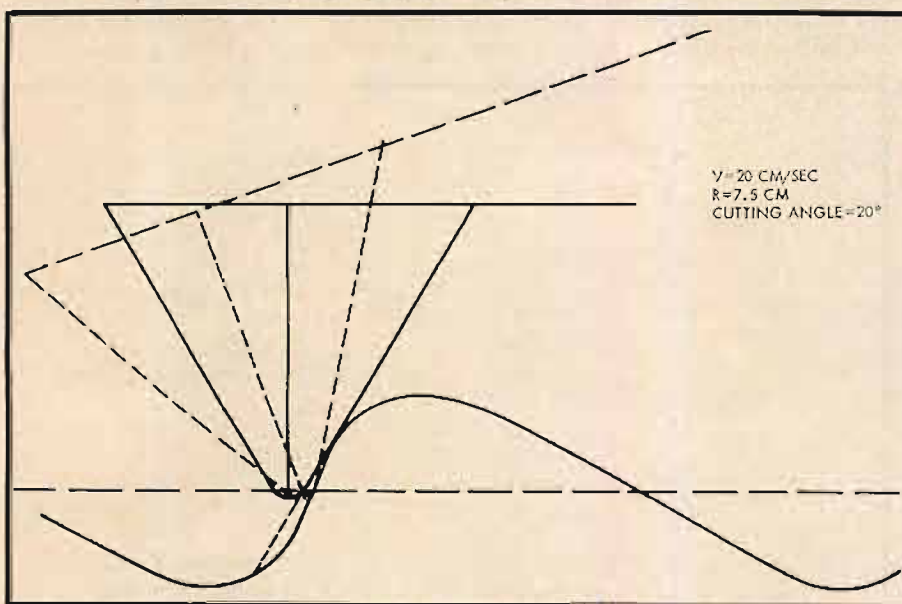


Fig. 9. Graphic representation of what happens when the stylus angle is different than the cutting angle. This indicates that the stylus should be tipped back rather than forward as is commonly believed.

value of Z can be obtained with the integration of a_2 's delineation value under the angle φ over a wavelength of the low frequency, which gives:

$$Z = \frac{\cos \alpha}{\sqrt{\cos(\alpha + \varphi) \cdot \cos(\alpha - \varphi)}}$$

With the help of the sine relation used on triangle MNO, we obtain

$$b = \frac{a_2 \cos \alpha}{\cos(\alpha - \varphi)}$$

and used on triangle MSO,

$$c = \frac{a_2 \cos \alpha}{\cos(\alpha + \varphi)}$$

Inserting the values for b , c , and Z in Eq. (1), we obtain

$$IM = \left[\frac{\cos(\alpha - \varphi)}{\cos(\alpha + \varphi)} - \sqrt{\frac{\cos(\alpha + \varphi)}{\cos(\alpha - \varphi)}} \right] \cdot 100\%$$

α , which is the angle for the zero transmission of the low frequency, is found from

$$\tan \alpha = \frac{v \sqrt{2}}{c}$$

where v is the effective recording speed in cm/sec, and c the groove speed in cm/sec.

Development of the above assumes a considerable difference in the two frequencies, and that the sine curve for the lowest frequency in the points considered can be thought of as a straight line.

The above gives a basis for the determination of the degree of intermodulation as a function of the tracking-angle fault.

Figure 5 shows IM calculated for three different recording levels and a distance from the record center of 10 cm. The calculation is valid for intermodulation of the odd harmonics.

A calculation of the intermodulation of the even harmonics shows that these are unimportant in comparison with the modulation of the odd harmonics.

If Fig. 1 and Fig. 5 are compared it is seen that considerable harmonic and intermodulation distortion appears if the vertical cutting angle and the vertical tracking angle of the pickup are not the same.

On the basis of two intermodulation test records produced by Ortofon, measurements have been made of a number of playback cartridges. The results are in Table II. The principle of the B & O pickup is shown in Fig. 6.

The results are anything but encouraging. From the measured values it is possible to predict with reasonable accuracy what angle the stylus cantilever makes with the record surface, if all the data for the record is known.

The variations in vertical cutting angle

(Continued on page 88)

TRACKING ANGLE

(from page 24)

from one record to the next also cause problems of channel separation. It is surprising, but frequently different amounts of crosstalk can be measured with the various records. Sometimes crosstalk is high from the left to the right channel, and low from the right to the left channel, and vice versa.

Figure 7 demonstrates what happens when the pickup is incorrectly positioned. The amount of channel separation will vary with the angle α . If everything is correct in both cutting and playback, two identical curves will be obtained for crosstalk on the left and right channels. However, measurements show that two identical curves are not obtained in all cases. This can be due to geometrical faults in the construction of the pickup, but if these are eliminated it is found that widely differing results are obtained when measuring the various test records.

Figure 7 shows a drawing of the stereo groove. ϕ is the vertical tracking angle and β is the cutting angle. x is 45 deg., the half angle of the angular distance between the two minimum points for the two curves for crosstalk as a function of the angle variation α .

If we assume that the cutting direction is 45/45 in the cutting plane, there is the following relation between the three angles:

$$\tan x = \frac{\cos \phi}{\cos \beta}$$

If we know ϕ and measure x we can thus find β .

Figure 8 gives these curves for various phonograph records. The B & O pickup was used in measuring these.

Since the vertical cutting angle varies from record to record, it is not possible to find any ideal pickup construction until standards can be agreed on.

The fact that the vertical cutting angle is in reality not vertical results in the

determination that the stylus tip should not be vertically oriented. Figure 9 shows what happens if the stylus angle is not in agreement with the cutting angle. This is a point which is frequently difficult to impress on people, even professionals. Generally there is the feeling that a pickup stylus should angle forward very slightly in order to avoid damaging the record. In reality this is a great misunderstanding. Due to the recording conditions, the stylus tip should in reality point in the opposite direction, and exactly as much as the cutting angle varies from the vertical line.

After a cold and sober theoretical consideration, the stereophonic phonograph records should in reality be intolerable to listen to. However, practice reveals a different situation. Even though the experienced ear can probably hear the greater distortion, there is no doubt that the stereophonic effect is such a great advantage that considerably more distortion can be tolerated than is the case with mono records. On the basis of listening tests it seems that such high demands for distortion reduction in stereo systems are unnecessary as compared with single-channel systems. This should not draw attention away from the sources of faults that can be removed with the greatest ease by merely establishing standards.

In the IEC-publication 98 and 98-1, which contains recommendation for commercial stereophonic records, the problem about the cutting angle is not mentioned. However this publication is being revised. At the IEC-meeting in Helsinki last year the Danish delegation proposed

to standardize this angle at 15 deg.:

(This proposal was made in Europe before the essentially European committee. See the Editorial for further comments about the status in the U. S. Ed.)

The proposal contains the following definition of the nature of the groove:

"The stereophonic groove shall carry two channels of information. The two channels shall be recorded in such a manner that they can be reproduced by movement of a reproducing stylus in two directions at 90 deg. to each other and at 45 deg. to a radial line through the stylus tip and the center of the disc.

"The reproducing stylus motion shall be tangent to or lie in a plane through the stylus tip and the record center, inclined at a nominal angle of 15 deg. clockwise to the normal through the stylus tip as viewed from the center of the disc."

It is hoped that the changing of Publication 98 and 98-1 will be confirmed as soon as possible, and that the different record makers will adopt this standardization as soon as possible. Æ

REFERENCES

- C. D. O'Neal, "The pyramid stylus," *IRE Transactions on Audio*, December 1959.
- M. S. Corrington and T. Murakami, "Tracing distortion in stereophonic disc recording," *RCA Review*, June 1958.
- C. C. Davis and J. G. Frayne, "The Westrex stereo disc system," *Proceedings of the IRE*, October 1958.
- B. B. Bauer, "Tracking angle in phonograph pick-ups," *Electronics*, March 1945.
- J. A. Pierce and F. V. Hunt, "On distortion in sound reproduction from phonograph records," *J.A.S.A.*, July 1938.
- Erling P. Skov, "Stereo disc problems," *A.E.S. Journal*, January 1960.