Groove Deformation and Distortion in Records*

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The elastic and plastic deformation of vinyl record compound under indenters of various profiles has been studied in large-scale tests. Curves of total depth of penetration versus load have been used to calculate the net distortion on record playback. In general, in the lower treble, net distortion is less, and in the upper treble, net distortion is greater than tracing distortion alone. This is important for attempts to reduce tracing distortion by inverse predistortion of the recorded signal. Nylon was also studied as a material with contrasting mechanical properties to vinyl. Further light has been shed on the nature of translation loss.

INTRODUCTION: In the playing back of records, tracing distortion is serious, as it can reach very high values. The original groove in the lacquer master is cut by a chisel-shaped cutter of 90° included angle, but the record is played back with a curved stylus. Thus it follows a different path from the cutter, and the difference, and hence the distortion, is most severe at high frequencies and at the lowest record speeds, that is, near the center of the record. By reducing the stylus radius, tracing distortion is reduced, and to avoid excessive deformation of the record groove, the lateral radius is increased, giving an elliptical or biradial stylus. Mathematical analyses of tracing geometry (assuming that the groove is rigid) have been made by Hunt [1], [2], Corrington [3], [4], and Cooper [5].

It is also known that there is considerable elastic and plastic deformation of the record groove under the load of the stylus [6]–[9], but the effect of this on the signal is not accurately known. Obviously it constitutes distortion which may add to or counteract tracing distortion. For static indentations, the elastic range is covered by the Hertz equations, which show that the elastic limit is reached at a load of 3 milligrams on a 12.7-μm (0.0005-inch) radius indenter on a flat surface of vinyl record compound. No solution exists for the plastic range, especially for sliding indentation with friction. Any solution is likely to be very long and cumbersome to use.

Considerable information is available on the widths of tracks made by indenters, but little on depths, these being much more difficult to measure, especially on the very small scale of a record groove. Walkling [10] has measured the mechanical impedance of vinyl surfaces by means of a vibrating pickup, but there is no simple way of converting his results to the required curve for load versus depth of penetration under load. White [11] has devised a mathematical conversion which suggests that at very low loads, the groove is more compliant than given by the Hertz equations; at high loads, in the fully plastic range, his results suggest that the material is even less compliant than a fully elastic material would be. The apparent behavior at low loads might be due to flattening of the surface asperities prior to "bedding down" on to solid material; at high loads, residual internal stresses, caused by rapid cooling, may increase the apparent hardness.

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The total depths under load, measured from the original surface, were therefore determined in large-scale tests over the appropriate range of loads, thus avoiding "noise" due to surface roughness of the groove. The material was slowly cooled to avoid residual stresses. Results represent the basic mechanical properties of the material without extraneous factors and enable the deformation and distortion to be calculated for record grooves. The deformation of the groove under load itself alters the load on the stylus, which in turn alters the deformation, etc., etc. The calculation is thus iterative, and a computer was used for this purpose.

1. MECHANICAL PROPERTIES OF RECORD COMPOUND

A preliminary investigation was made of the mechanical properties of the vinyl chloride-acetate co-polymer used for records. This contains about 16% of acetate to lower the processing temperature, together with small quantities of carbon black pigment, stabilizers, and lubricants (to assist removal from the mould), but no plasticizer. The material was in the form of blocks about 1 cm thick, made by compression moulding. All the tests were carried out at 18–20°C to avoid variations in properties due to temperature.

Compression tests were made on cylinders machined from the blocks, and curves are given in Fig. 1. The stress is plotted as nominal stress (= load/original cross-sectional area) and true stress (= load/current cross-sectional area). The latter gives a better indication of what the material is doing. The initial portion of the curve is elastic, the slope giving Young's modulus of elasticity. After yielding, the load which the specimen can support drops, and even after considerable deformation, (measured as contraction in height = (original height − final height)/original height × 100%), the original yield stress is not regained, that is, the material work-softens before eventually beginning to work-harden. This is unusual, although there are many materials which show very little work-hardening. This must affect the record distortion characteristics, and nylon was chosen as a contrasting material, as it is known to work-harden considerably. In this case, compression moulding cannot be used due to excessive oxidation, and injection moulding gives unsoundness in thick sections. The blocks were therefore cast from hot monomer, which polymerized in the mould to nylon 66. Similar compression tests were made and curves are given in Fig. 1, and show typical work-hardening from the onset of yielding.

A large number of static and sliding indentations were made on the two materials, which showed that they were fully elastic at sufficiently low loads and did not behave differently in principle from other materials. This has been fully reported elsewhere [12].

2. DYNAMIC SLIDING INDENTATION TESTS

Blocks with a flat as-moulded surface were mounted on the faceplate of a lathe. The surface speed was 35–45 cm/s, the properties varying little over the range of interest. The indenter of hardened steel was mounted on a rigid lever arm pivoted on the saddle. The load was applied by means of pulley, cord, and weights. A dial gauge reading to 1/10 000 inch was mounted adjacent to the indenter, bearing on untested material adjacent to the tracks made by the indenter. The spherical indenter was of 1.27-mm radius, corresponding to a 12.7-μm (0.0005-inch) radius stylus. Indenters corresponding to biradial styli of 18/9 μm (0.0007/0.00035 inch) and 20/5 μm (0.0008/0.0002 inch) radius styli were also used. So-called elliptical styli are usually made by grinding flats on a conical stylus. The end is then polished to remove sharp corners and to produce the desired radii. The exact profile at the point of contact with the record may be uncertain. In the present case, the indenters were truly biradial and to the correct radii. An indenter equivalent to 70/7 μm was also included, representing the Shibata and similar styli.

Curves are given in Figs. 2 and 3 for 1, 2, 5, and 10 playings. Over most of the range of interest, the curves are straight on a log–log scale and the corresponding equations are given in Table I. The slope of the vinyl curves decreases with repeated playing, whereas for nylon the slope does not change. This is a function of the greater work-hardening of the nylon, for which the slope is conveniently 1. The 70/7-μm equivalent indenter gave results very similar to the 18/9-μm indenter.

As a check on these large-scale tests, tracks were made on the central flat portion of a record at loads of 4, 6, 8, 10, and 12 grams, using a 25.4-μm radius stylus at a record speed of 36 cm/s. The widths of the tracks were measured, using a microscope with graticule eyepiece and

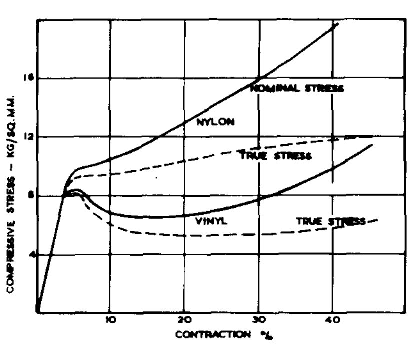


Fig. 1. Compressive stress-strain curves on vinyl and nylon.

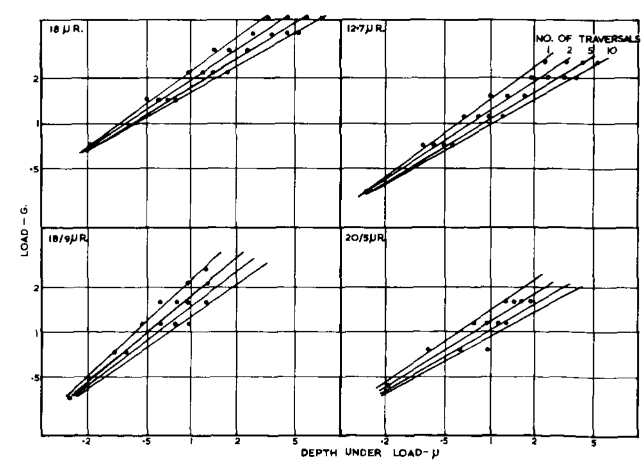


Fig. 2. Dynamic load versus penetration, vinyl.

vertical illuminator. These track widths are compared with the equivalent widths from the large-scale tests, (Table II). Agreement is good, considering the difficulty of making accurate measurements on very small tracks.

Lewis [13] has produced excellent micrographs of record grooves, using the scanning electron microscope. These provide a further check on the present tests. A playing weight of 5 grams was used, corresponding to 3.54 grams on each groove wall. The corresponding track width expected from large-scale tests for one playing would be 14.8 μm. Lewis's maximum and minimum track widths for one playing of a groove with a sine wave test signal are 17.7 and 11.8 μm, giving a mean of 14.8 μm.

3. DEFORMATION OF CURVED SURFACES

To measure depths of penetration at high speed on curved surfaces is difficult, so slow-speed tests were made to obtain ratios of (depth on curved surface) to (depth on flat surface). Specimens were moulded with convex and concave profiles of various radii, and the depths were measured while traversing under load, using lever arm and dial gauge as before. The largest possible indenter was used to give the greatest accuracy. The spherical indenter was of 2.38-mm radius, representing a 12.7-μm radius stylus, and corresponding biradial indenters were used. There was considerable scatter with the vinyl. To reduce this, results were repeated several times, and between each set of 10 traverses, the depth on the adjacent flat surface was measured. This also reduced possible scatter due to temperature and humidity variations and variation in material properties from point to point. The scatter on the vinyl, in contrast to the nylon, was doubtless due to the lack of work-hardening. This took the form of instability or juddering with increasing ellipticity of the indenter. This gave some variation in track depth. With excessive loads, the biradial indenters dig in and act as a cutting tool, with the formation of a chip.

The results represent over 20 000 traversals. Values may be plotted as the ratio (depth on curved surface) to (depth on flat surface) versus load and as ratio versus radius of profile. These form a cross check, as the ratio versus load curves must be drawn through scattered points such that the ratio versus radius curves are smooth. The latter curves are given in Figs. 4–11. In general, the ratios are lower for the nylon, that is, geometry has less effect on depth of penetration. This again is doubtless due to the work-hardening of the nylon.

4. COEFFICIENT OF FRICTION

The coefficient of friction varies according to measuring conditions and may vary considerably over different parts of a given record. Rangabe [14] has measured friction in

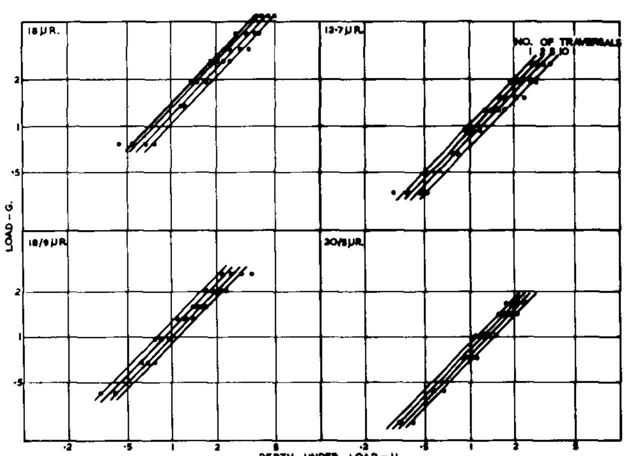


Fig. 3. Dynamic load versus penetration, nylon.

Table I. Equations for dynamic depth versus load.

Depth [μm] = a (Weight w [gram])^b	18-μm Radius	12.7-μm Radius	18/9-μm Radius	20/5-μm Radius
Vinyl				
1 playing	$0.30w^{1.46}$	$0.59w^{1.46}$	$0.43w^{1.03}$	$0.74w^{1.25}$
2 playings	$0.33w^{1.57}$	$0.70w^{1.57}$	$0.50w^{1.12}$	$0.91w^{1.36}$
5 playings	$0.38w^{1.68}$	$0.85w^{1.68}$	$0.57w^{1.22}$	$1.09w^{1.47}$
10 playings	$0.42w^{1.79}$	$1.00w^{1.79}$	$0.64w^{1.33}$	$1.29w^{1.58}$
Nylon				
1 playing	$0.66w$	$0.94w$	$0.83w$	$1.13w$
2 playings	$0.75w$	$1.06w$	$0.93w$	$1.25w$
5 playings	$0.84w$	$1.18w$	$1.03w$	$1.38w$
10 playings	$0.92w$	$1.30w$	$1.13w$	$1.50w$

Table II. Comparison of tracks from pickup with large-scale tests.

Weight on pickup 25.4-μm Radius Stylus [gram]	Measured Track Width [μm]	Expected Track Width from Large-Scale Tests [μm]
12	27.5	29
10	25	27
8	22	22
6	21	18
4	16	15

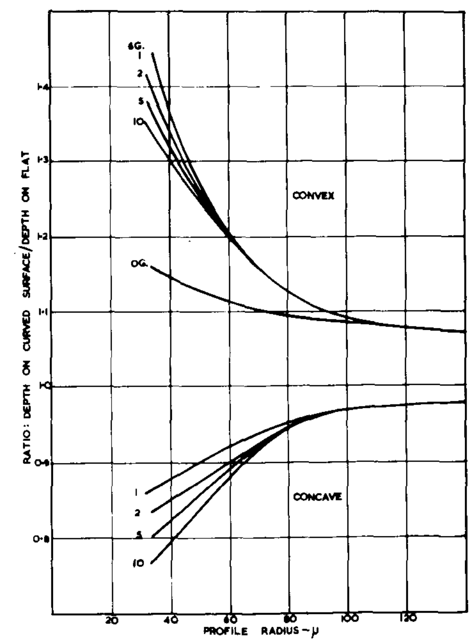


Fig. 4. Depth ratio versus profile radius, vinyl 18-μm radius stylus.

the record groove under actual playing conditions. His equipment consists of a modified "Trutrak" parallel tracking device. This has an arm mounted on a float in an oil bath. The arm is located longitudinally by means of magnetic repulsion. The frictional drag on the stylus moves the arm forward against the magnetic repulsion, and the value can be read off a scale. The system is easily calibrated by means of weights. The friction varies very little with speed and weight, and mean values on flat surfaces for the various styli are given in Table III.

It will be noted that the coefficient of friction increases with increasing ellipticity of the stylus. Over most of the range of loads of interest, styli work in the fully plastic range of the vinyl. The contact pressure is about 3 times the yield stress and is almost constant with load. Under a given load, the area of contact and the contact pressure will be similar for each indenter. The differences in the coefficient of friction are therefore a function of geometry. A stylus with a very small longitudinal radius ploughs out a groove of larger cross section than a spherical stylus, thus giving a higher coefficient of friction.

5. PARAMETERS FOR CALCULATION

It was considered by Hunt [15] that an acceleration of $1000g$ was a reasonable maximum requirement for tracking. This is for a lateral signal, corresponding to $707g$ for each groove wall. This gives a minimum trace radius at 10 kHz at the outer edge of the record of 36 μm.

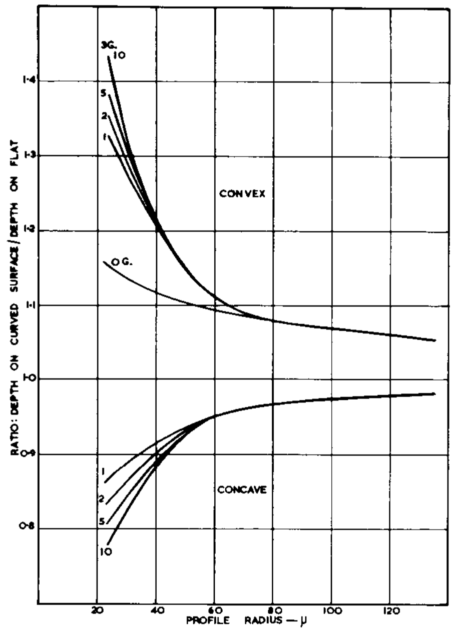


Fig. 5. Depth ratio versus profile radius, vinyl 12.7-μm radius stylus.

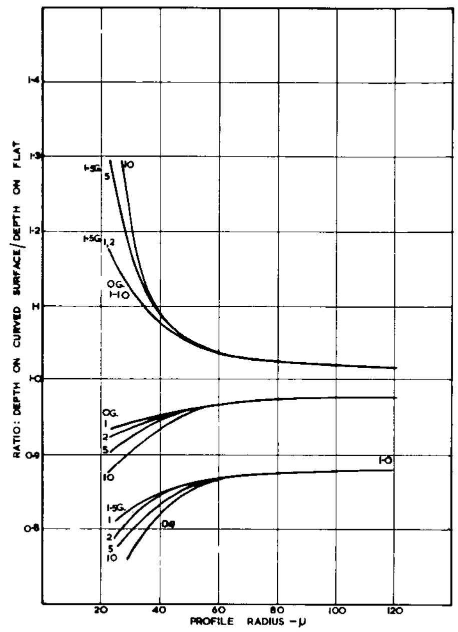


Fig. 7. Depth ratio versus profile radius, vinyl 20/5-μm radius stylus.

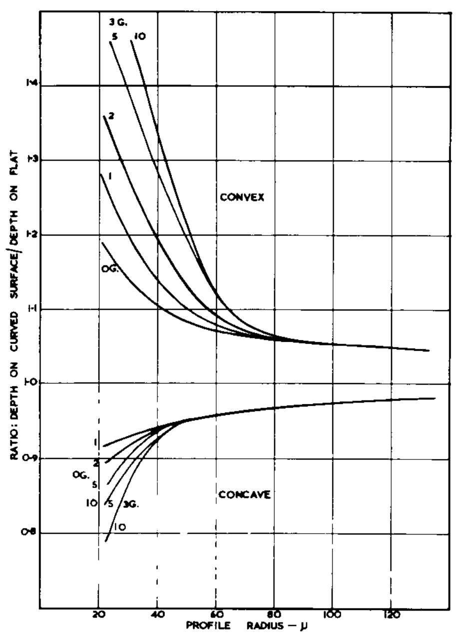


Fig. 6. Depth ratio versus profile radius, vinyl 18/9-μm radius stylus.

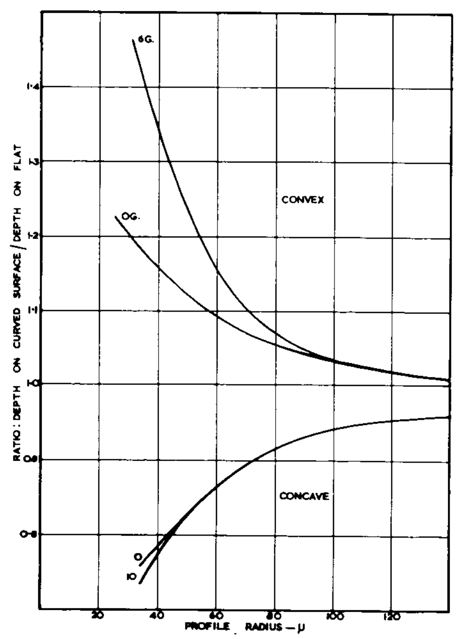


Fig. 8. Depth ratio versus profile radius, nylon 18-μm radius stylus.

Curvature overload occurs when the trace radius is as small as the stylus radius, but there may be serious damage to the groove before this point is reached. In slow-speed tests, digging in with the formation of a chip occurs at a trace radius of 18–25 μm. At the inner edge of the recorded area, the corresponding minimum trace radius would be less than 9 μm, so that the maximum playable acceleration will be much less than 707 g, except perhaps with the 20/5-μm stylus.

The worst case for distortion would be with the signal on one wall only. With equal signal on both walls in phase, the lateral case, the system is in push–pull, so that second-harmonic tracing distortion is canceled. In the vertical case the signals are out of phase. It is convenient to compare results by taking similar nominal accelerations. Thus by taking values of amplitude proportional to 1/(frequency)^2 (equivalent to a frequency response of -6 dB per octave), the maximum nominal acceleration and minimum trace radius are the same at all frequencies. Furthermore, the tracing distortion is the same at all frequencies. The velocity of the cut varies as 1/frequency, so that the resistive component of the load will be higher at the lower frequencies.

In comparing pickups, the tip mass in each case is 1/3000 of the playing weight, such that one third of the playing weight would be needed to track an acceleration of 1000 g. The compliance in each case is such as to need one third of the playing weight to track the maximum amplitude of 0.005 cm (at low frequencies). Resistance values were taken proportional to playing weight and give Q of 1.25–7.0 at the top resonance of the tip mass with groove compliance. Values of parameters are given in Table III.

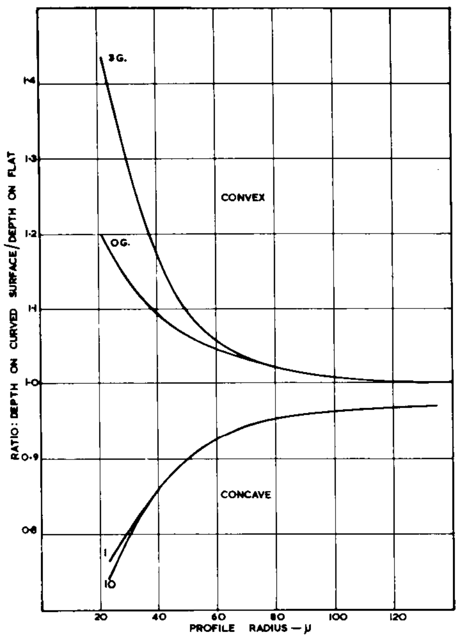


Fig. 9. Depth ratio versus profile radius, nylon 12.7-μm radius stylus.

6. TOP RESONANCE

The compliance of the groove at a given playing weight is given by the tangent modulus or slope of the load–penetration curve, and values have been used to calculate the top resonances (Table IV). Some of the resonances are lower in frequency than might be expected and decrease with repeated playing. A check was made on a gliding tone record, DGG 1099111, using a Shure M55E pickup with 0.0007/0.0002-inch stylus at 3-gram playing weight. The top resonance was at 15 kHz and altered very little with repeated playing. It has been argued previously [16] that although considerable plastic deformation takes place, the top resonance may be governed by elastic properties. On loading, the material follows the load–penetration curve. At any point it has deformed and/or work-hardened to support that load. On unloading it is elastic up to the particular load and springs back according to the elastic

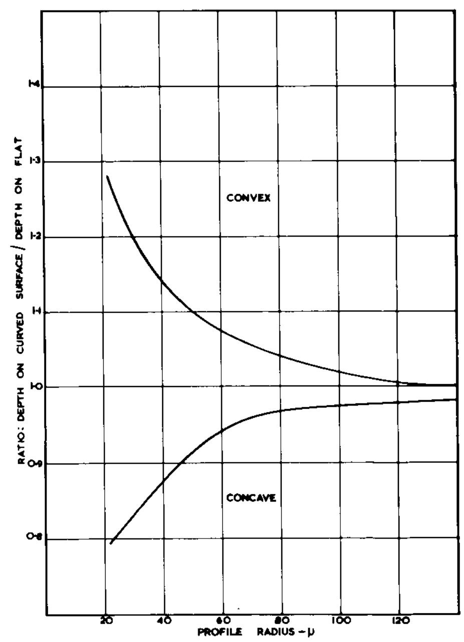


Fig. 10. Depth ratio versus profile radius, nylon 18/9-μm radius stylus.

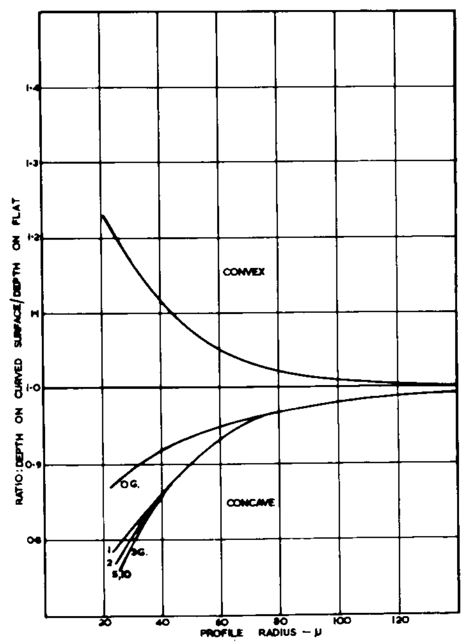


Fig. 11. Depth ratio versus profile radius, nylon 20/5-μm radius stylus.

Table III. Parameters for calculations.

Frequency [kHz]	10		7.07		5		3.54	
Record velocity [cm/s]	50	25	50	25	50	25	50	25
Amplitude [μm]	1.75	—	3.51	—	7.01	—	14.03	—
	0.88	0.88	1.75	1.75	3.51	3.51	7.01	7.01
	0.44	0.44	0.88	0.88	1.75	1.75	3.51	3.51
	—	0.22	—	0.44	—	0.88	—	1.75
Velocity of cut [cm/s]	11.0	—	15.6	—	22.0	—	31.2	—
	5.5	5.5	7.8	7.8	11.0	11.0	15.6	15.6
	2.8	2.8	3.9	3.9	5.5	5.5	7.8	7.8
	—	1.4	—	2.0	—	2.8	—	3.9
Acceleration g [cm/s^2]	707	—	707	—	707	—	707	—
	354	354	354	354	354	354	354	354
	177	177	177	177	177	177	177	177
	—	88.5	—	88.5	—	88.5	—	88.5
Minimum trace radius [μm]	36	—	36	—	36	—	36	—
	72	18	72	18	72	18	72	18
	144	36	144	36	144	36	144	36
	—	72	—	72	—	72	—	72
Stylus radius [μm]	18		12.7		18/9		20/5	
2nd-harmonic tracing distortion [%] (all frequencies)	25	—	17.7	—	12.5	—	6.9	—
	12.5	50	8.8	35.4	6.3	25	3.5	13.9
	6.3	25	4.4	17.7	3.1	12.5	1.7	6.9
	—	12.5	—	8.8	—	6.3	—	3.5
3rd-harmonic tracing distortion [%] (all frequencies)	9.4	—	4.7	—	2.4	—	0.7	—
	2.4	37.5	1.2	18.8	0.6	9.4	0.2	2.9
	0.6	9.4	0.3	4.7	0.2	2.4	0.04	0.7
	—	2.4	—	1.2	—	0.6	—	0.2
Coefficient of friction								
Vinyl	0.24		0.24		0.31		0.36	
Nylon	0.16		0.16		0.17		0.21	
Pickups	Playing Weight [gram]		Compliance [cm/dyn]		Effective Tip Mass [mg]		Resistance [mechanical ohm]	
	3.0		5×10^{-6}		1.0		44	
	1.5		10×10^{-6}		0.5		22	
	0.75		20×10^{-6}		0.25		11	
Number of playings 1, 2, 5, 10								

condition, and does not follow the loading curve. Using the elastic condition, good agreement is obtained with actual values of top resonance with spherical styli on certain pickups where tip mass is accurately known, but agreement with biradial styli is less satisfactory. It is not clear on some pickups just where the top resonance is, as there may be other peaks in some designs due to the presence of other compliances. Also there may be an electrical peak and cutoff. The inductance in many designs is typically 0.5 H, and the self-capacity of the cable may be 120 pF per channel. This gives a low-pass filter cutting off above 20 kHz. Higher shunt or cable capacities are recommended by the manufacturers in some cases. Further work is needed to determine the exact nature of the groove compliance. The tangent modulus is used in the present calculations.

7. CALCULATION OF DISTORTION

The method of calculation is iterative, starting with the tracing distortion curve and successively producing modified deformed curves until convergence to the true deformation has been achieved. A flow diagram of the process is shown in Fig. 12, and the action of the boxes is amplified below.

Box 1. The tracing distortion curve is obtained purely from the geometry of the system in the usual way (assuming no deformation) and is calculated at 1° intervals from 0° to 360°, based on an original cosine curve, this being easier to handle than a sine curve.

Box 2. Only the first three harmonics have been considered, since

1) higher harmonics will be small and most will be well above the audio range and the working range of the pickup,

2) very high accuracy of results would be necessary to detect small amounts of higher harmonics—the amplitude of each harmonic has to be multiplied by its own number, as the pickup has a velocity characteristic

3) the higher harmonics are likely to make convergence more difficult. The Fourier coefficients were determined using a standard algorithm [17].

Box 3. In order to ensure convergence of the process, the difference between the newly calculated and the previous Fourier coefficients for the kth harmonic, expressed as a complex number, is modified by a factor $(1 - mC\omega^2) + jCr\omega$, where C is an average value for the record compliance, m the effective mass at the stylus tip, r the mechanical resistance of the pickup, and $\omega = 2\pi kf$, where k (= 1, 2, 3) is the harmonic number and f the frequency.[1]

Box 4. Convergence is achieved when the percentage distortions from the original cosine curve of the two latest deformed curves differ by less than 1% in the first two harmonics and by less than ½% in the third harmonic.

Box 5. Ordinates for the new deformed curve are calculated at 1° intervals by first obtaining a value for the dynamic load, which is a function of the static load, acceleration, stiffness, and resistance and then calculating the deformation from the tracing distortion curve, which is a function of load, friction, curvature, and slope.

This has been written as a Fortran program and run on the ICL 1904S* machine at Bradford University. Results are plotted in Fig. 13 for vinyl and Fig. 14 for nylon. The theoretical tracing distortion is indicated by means of horizontal bars. The change in level of fundamental from the recorded amplitude is expressed in decibels. The second and third harmonics are expressed as a percentage, based on the playback level of the fundamental, rather than the recorded level. The profile of a typical groove under load is shown in Fig. 15.

Table IV. Calculated top resonances of pickups [kHz].

	Stylus Radius			
	18 μm	12.7 μm	18/9 μm	20/5 μm
Vinyl 3.0 grams				
1 playing	20.0	14.3	23.1	14.9
2 playings	17.7	12.1	20.1	12.3
5 playings	15.3	10.2	14.8	10.5
10 playings	13.5	8.7	13.0	8.9
Vinyl 1.5 grams				
1 playing	33.3	23.8	33.5	23.0
2 playings	30.5	20.9	29.7	19.8
5 playings	27.3	18.3	26.5	17.3
10 playings	25.1	16.3	23.9	15.4
Vinyl 0.75 gram				
1 playing	55.1	39.3	47.8	35.5
2 playings	52.4	36.2	43.7	31.7
5 playings	49.0	32.8	40.6	30.0
10 playings	46.7	30.3	38.0	26.6
Nylon 3.0 grams				
1 playing	19.4	16.2	17.3	14.8
2 playings	18.2	15.3	16.3	14.1
5 playings	17.2	14.5	15.5	13.4
10 playings	16.4	13.8	14.8	12.8
Nylon 1.5 grams				
1 playing	27.4	23.0	24.5	21.0
2 playings	25.7	21.6	23.1	19.9
5 playings	24.3	20.5	21.9	18.9
10 playings	23.2	19.6	21.0	18.2
Nylon 0.75 gram				
1 playing	38.8	32.5	34.6	29.7
2 playings	36.4	30.6	32.6	28.2
5 playings	34.4	29.0	31.0	26.7
10 playings	32.9	27.7	29.7	25.7

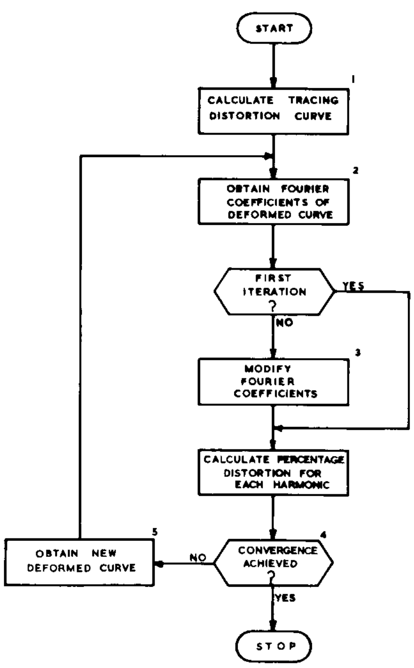


Fig. 12. Flow diagram of calculations.

8. DISCUSSION OF RESULTS

In general, with vinyl the net second-harmonic distortion is less than tracing distortion at the lower frequencies, and higher at the higher frequencies. This might be a function of the increasing velocity and resistance component at the lower frequencies. This was checked by reducing the resistance to zero in a suitable case, that is, where fundamental, second, and third harmonics are well below the top resonance, which would be undamped. Both second and third harmonic distortion were increased by reducing the resistance, but the trend of increasing distortion with increasing frequency was still present (Fig. 16).

The effect of repeated playing is usually to reduce the distortion. With a playing weight as low as 0.75 gram the effect of repeated playing is much less; deformation is fairly small, and the net distortion approaches the tracing distortion in most cases. The effect of biradial styli is to reduce the distortion in most but not all cases. The effect of friction is shown in a typical case recalculated with zero friction (Fig. 17). Friction reduces the second harmonic but increases the third harmonic.

The effect of increasing the playing weight, other pickup parameters remaining unaltered, is shown in a typical case in Fig. 18. Woodward and Werner [18] found that increasing the playing weight (above that needed for proper tracking) decreased the intermodulation distortion, measured using two tones close together. In this case, the second harmonic has been reduced, but the third harmonic has been increased.

Attempts have been made to reduce distortion on playback by predistorting the signal in the inverse of the tracing distortion [19–22]. This ignores deformation and any change on repeated playback. It seems unlikely that

[1] Suggested by Dr. P. G. Craven.

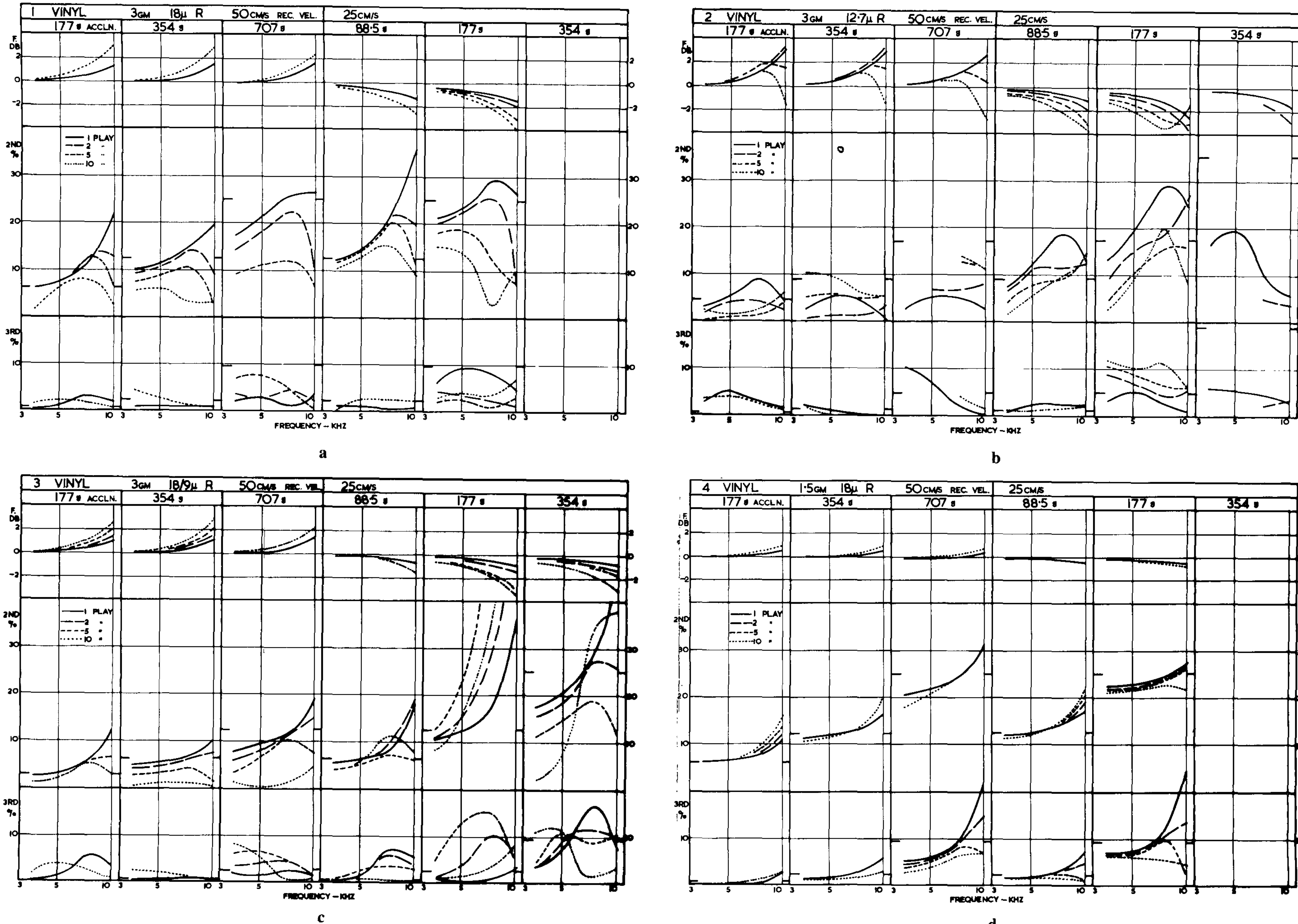
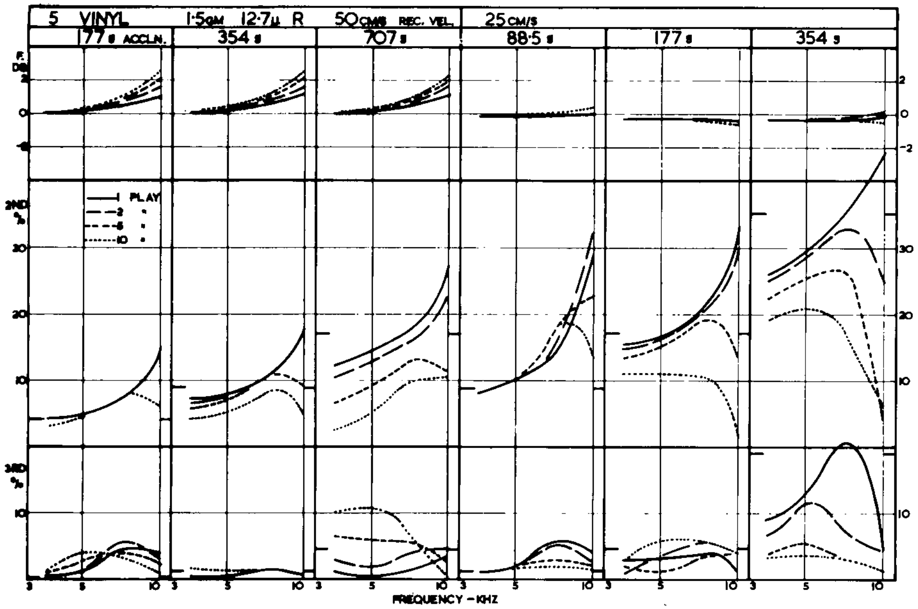


Fig. 13. Calculated change in fundamental level (dB) and second- and third-harmonic distortion (%) on playback of vinyl records at various nominal accelerations, playing weights, stylus radii, record velocities and number of playings.



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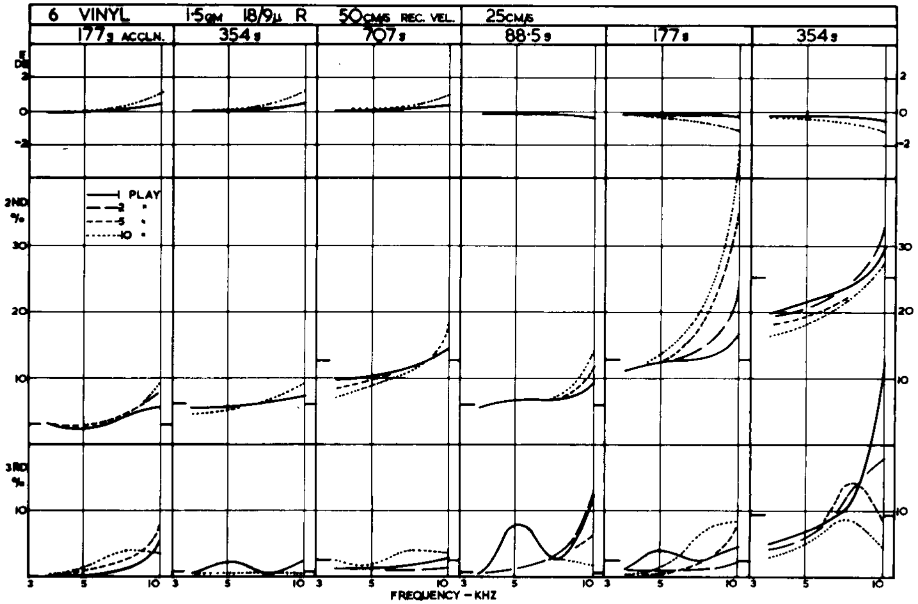

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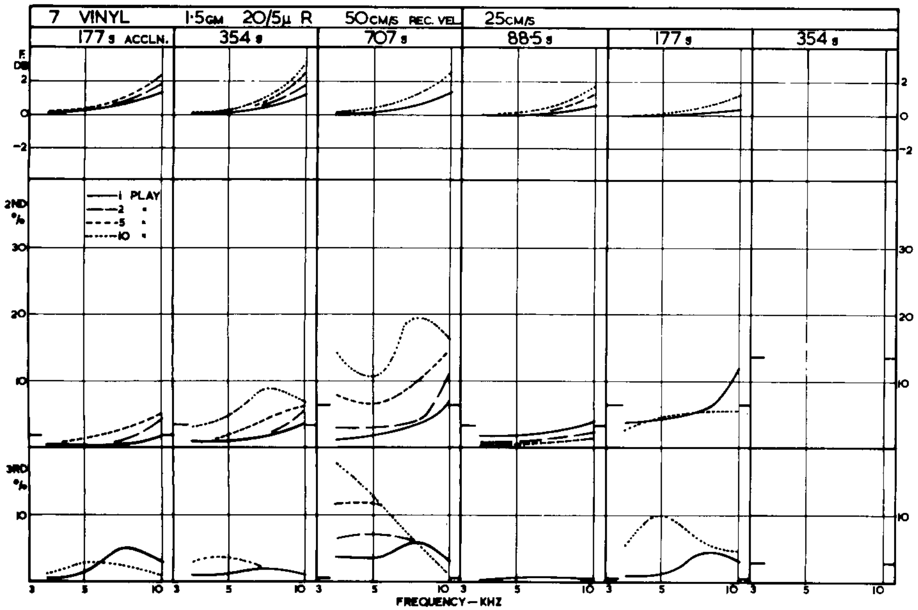

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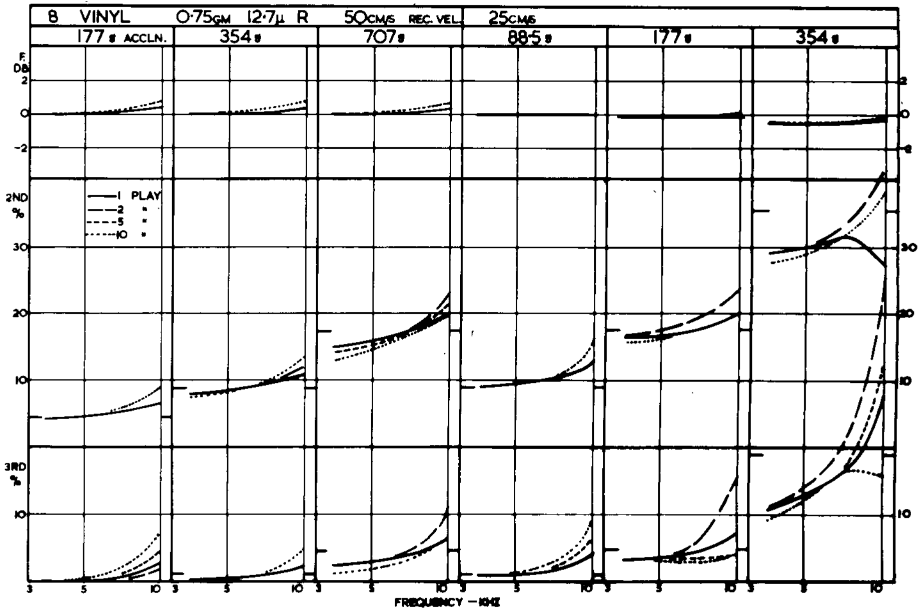

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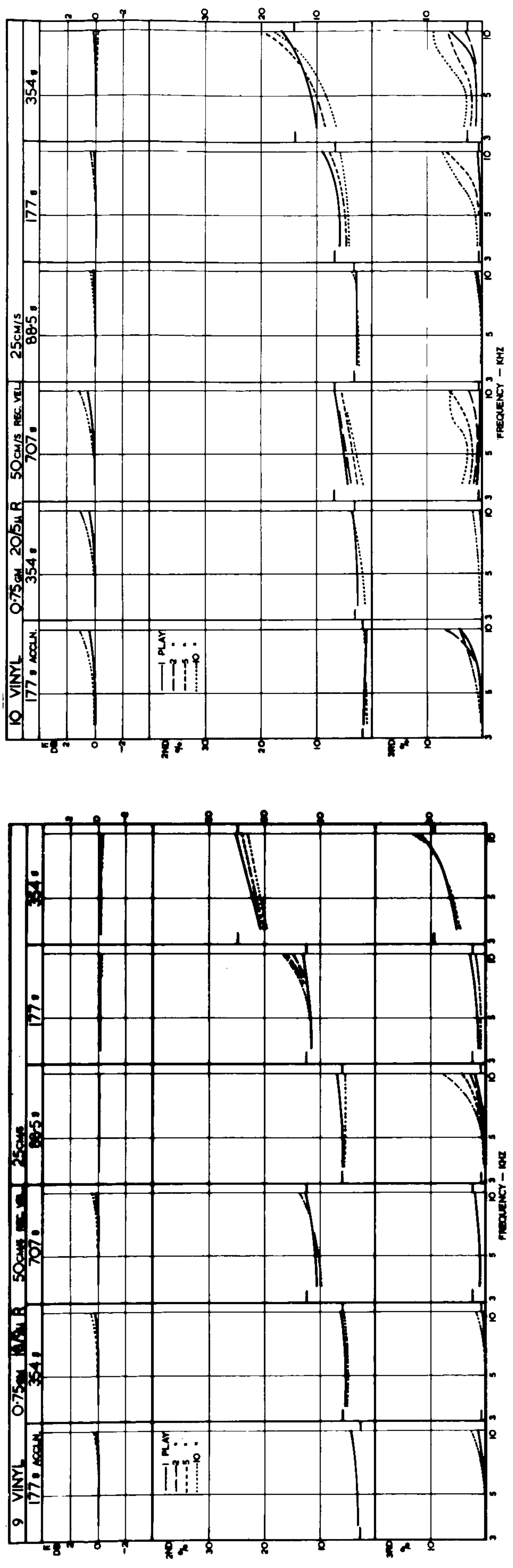
Fig. 13 continued



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i

Fig. 13 continued

this could be very successful with existing pickups although Cooper [23] has argued that such predistortion will itself give less deformation distortion. If a future generation of pickups could be produced with a (genuine) playing weight of ¾ gram or less, predistorting for tracing distortion only would be reasonably accurate, and the change with repeated playing would be small. With this playing weight, a biradial stylus would be used to give minimum tracing distortion in any case, as there would be no danger of excessive deformation or frictional damage to the groove.

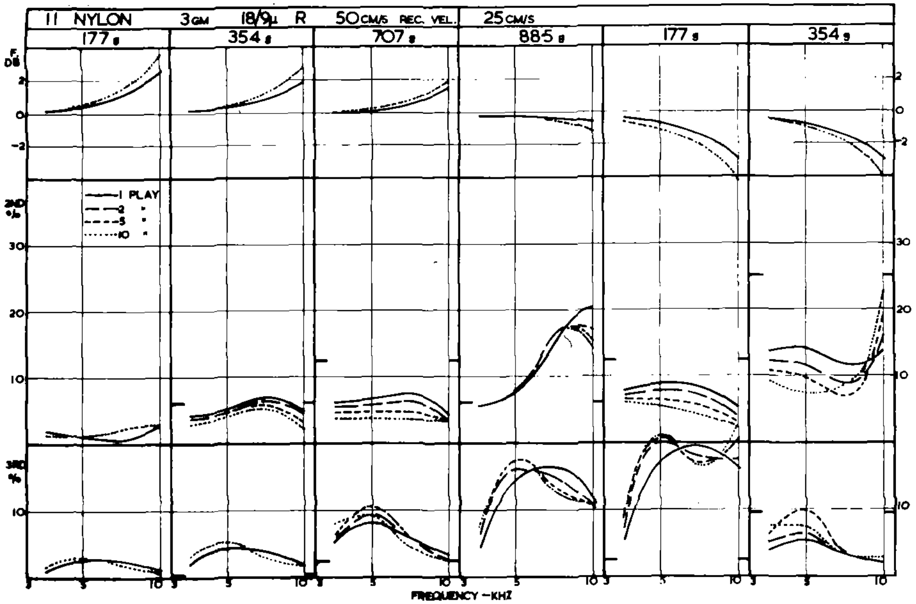
Nylon shows less change with repeated playing than vinyl, no doubt due to the work-hardening. Also, the second harmonic is lower than on vinyl under the same conditions, but the third harmonic can reach high values near the center of the record, although much of this will be inaudible. Whether using a material with a high rate of work-hardening is advantageous or not will depend on the particular case.

Comparison with shellac or harder materials would be of interest. The effect of a harder material was obtained by halving the compliance of nylon in a typical case. This gave less distortion at higher frequencies but more distortion at lower frequencies (Fig. 19).

9. PLAYBACK LOSS

It is well known that a high-frequency signal recorded near the center of the disc gives a lower output from the pickup than a similar signal recorded near the outside diameter of the disc. Hunt [15] has called this difference translation loss, caused by the curvature of the trace, such that the stylus would deform a convex curve more than a concave one, resulting in a net loss of signal. However, the present calculations clearly show that in addition to the treble droop at the inner diameter, relative to the mean level, there is a treble rise near the outer diameter of the record. A check test at an intermediate diameter, at 37.5-cm/s velocity, gave intermediate values. Omitting the curvature factors in a typical case (vinyl, 3 grams, 12.7-μm radius, 177g, 1 play) gave a rise of 4 dB at 10 kHz at both outer and inner diameters of the disc. The rise at the outside is due to acceleration forces. These act against the playing weight on the hills and with the playing weight in the hollows. The load and deformation are thus reduced on the crests (tending to preserve them) and are increased in the hollows (which are better able to withstand heavy loads). This increases the signal level obtained. The same applies to the inner diameter of the record, but it is obscured by the greater loss due to the greater curvature.

Another term which is sometimes used is scanning loss. This is the analogy with the gap-length effect in magnetic recording, the slit-width effect in the photoelectric playback of film sound tracks, and the aperture-loss effect in optical scanning for facsimile transmission. In these cases, the effect is purely geometrical, occurs in isolation, and is predictable. In record playback, the effect of the finite area of contact is all part of the deformation process, and there seems little point in trying to separate out some hypothetical component.



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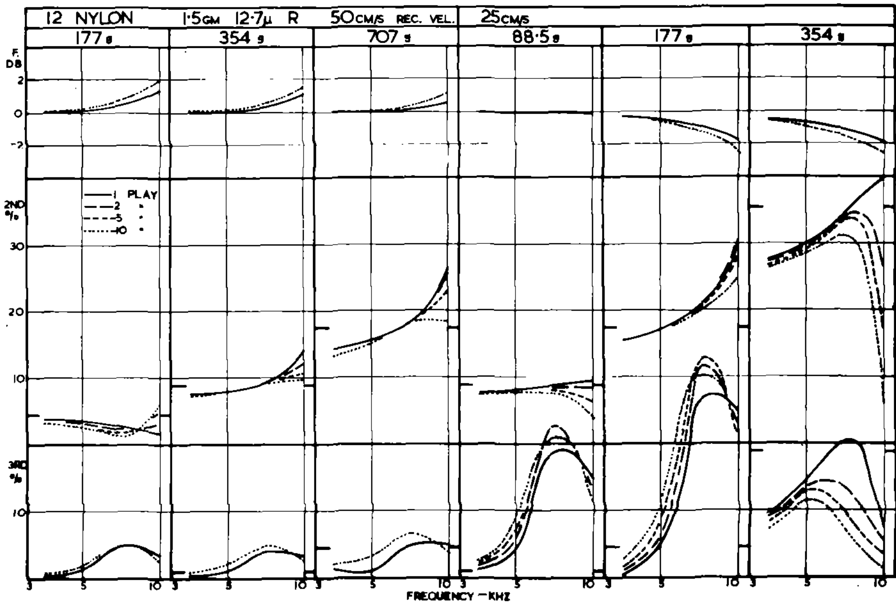

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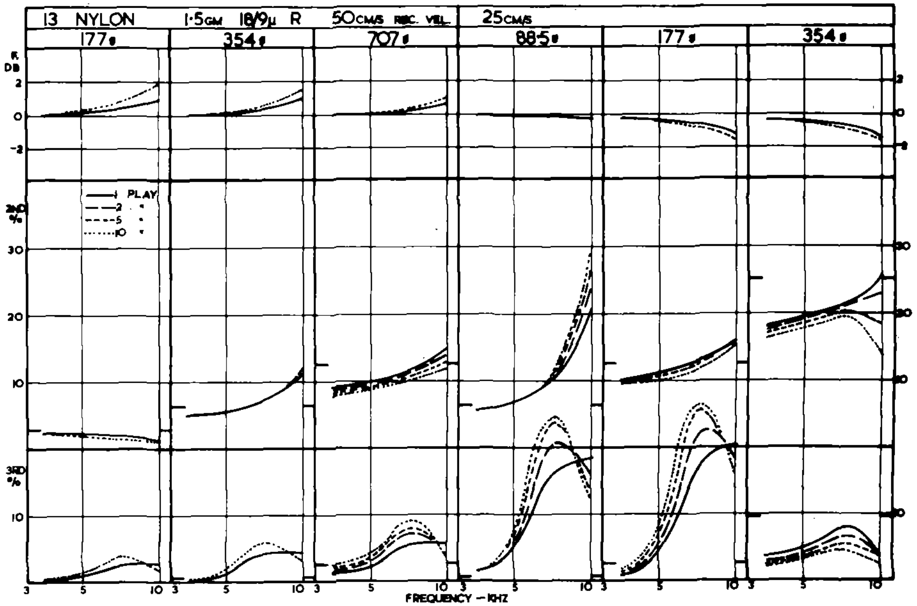

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Fig. 14. Calculated change in fundamental level (dB) and second- and third-harmonic distortion (%) on playback of nylon records at various nominal accelerations, playing weights, stylus radii, record velocities and number of playings.

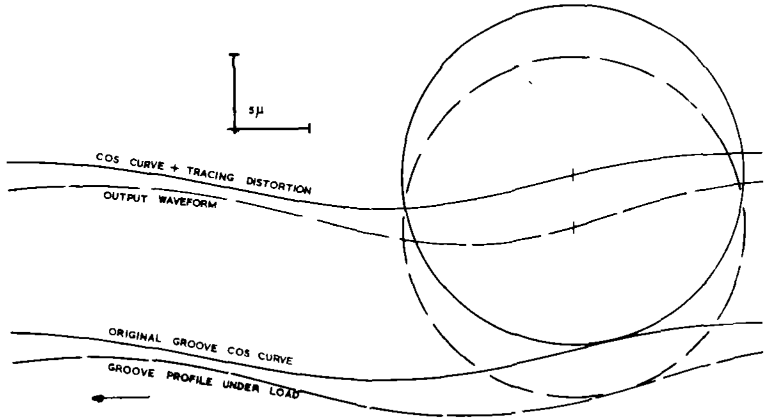

Fig. 15. Profile of typical groove under load.

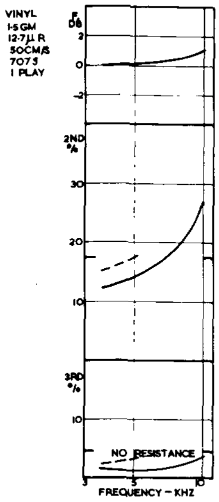

Fig. 16. Effect of resistance.

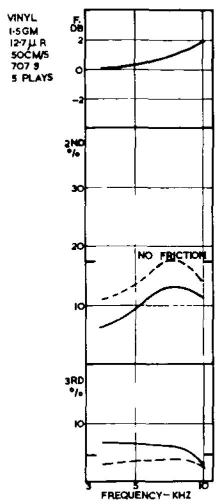

Fig. 17. Effect of friction.

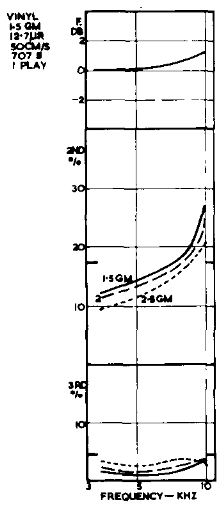

Fig. 18. Effect of increasing playing weight.

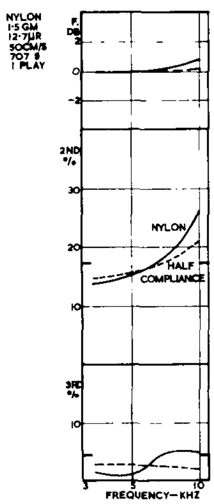

Fig. 19. Effect of harder material.

10. FURTHER WORK

The need to elucidate the nature of groove compliance has already been stated. Comparison with practical test data is obviously called for. Predistortion and intermodulation distortion calculations of difference tones on two-tone signals are desirable. Similar work on metal would permit the effect of monitoring of the metal mothers to be determined.

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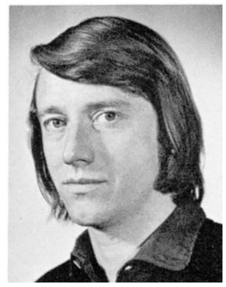

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