The Columbia Long-Playing Microgroove Recording System*

PETER C. GOLDMARK†, FELLOW, IRE, RENÉ SNEPVANGERS†, AND
WILLIAM S. BACHMAN‡, MEMBER, IRE

Summary—The Columbia LP (long-playing) microgroove recording system was developed to fill the need for music reproduction which would avoid interruptions not intended by the composer, and which would be of excellent quality at a reasonable cost. This all-important factor of cost and the public's familiarity with the handling of phonograph records made it desirable to solve the task on the basis of records, rather than tape or wire.

Standard 78-rpm records were originally designed to generate sound mechanically by direct transfer of energy from the groove of the record to the vibrating diaphragm. Because the entire acoustical energy had to be extracted from the grooves, these had to be quite rugged, and remained so up until now.

The new Columbia recording system was an inevitable outcome of the use of electrical amplification between the groove and the loudspeaker. Today, practically no mechanical energy needs to be extracted from the groove, and thus, for the first time, it has been possible to develop much finer grooves, permitting longer playing time and distortion-free reproduction.

INTRODUCTION

THE COLUMBIA LP[1] (long-playing) microgroove recording system was developed to provide uninterrupted music reproduction of better quality at a reasonable cost. This all-important factor of cost, together with the public's familiarity with the handling of phonograph records, made it desirable to solve the problem on the basis of disk records, rather than by tape or wire.

Standard 78-rpm records were originally designed to generate sound mechanically by direct transfer of energy from the groove of the record to the vibrating diaphragm. Because the entire acoustical energy had to be extracted from the grooves, these had to be quite rugged, and remained so until now. The weight of the diaphragm and armature, together with the acoustical reproducer, resulted in high vertical needle forces, requiring large stylus diameters. The latter made necessary the use of the high-speed turntable (78 rpm) in order to allow for a sufficient frequency range and a minimum of distortion. Today, practically no mechanical energy need be extracted from the groove, thus allowing a far greater latitude in the design of an improved system.

The fundamental principles of the Columbia LP records are the slow rotational speed of 33⅓ rpm, representing a time-saving factor of roughly 2.3; and finer grooves, up to 300 per inch.

PLAYING TIME

It was found that the average playing time for classical works is approximately 36 minutes. Nevertheless, standards were developed to accommodate as much as 50 minutes of playing time on a 12-inch record.

The following analysis establishes the optimum relationship between the inside and outside groove diameters for maximum playing time.

The variables used are:

d = inside groove diameter in inches
D = outside groove diameter in inches
R = revolutions per minute
N = total number of grooves
T = playing time in minutes.

The constants used are:

n = grooves per inch
$V_{\min}$ = minimum permissible linear groove velocity in inches per second.

The playing time T is equal to the total number of grooves N divided by the revolutions per minute R of the record.

$$T = \frac{N}{R}\cdot \tag{1}$$

N is a function of the number of grooves per inch and of the radial distance utilized:

$$N = n\left(\frac{D-d}{2}\right). \tag{2}$$

R is determined by the minimum recorded radius and the minimum permissible linear groove velocity:

$$R = \frac{60V_{\min}}{\pi d}\cdot \tag{3}$$

Substituting (2) and (3) in (1),

$$T = \frac{n\left(\frac{D-d}{2}\right)}{\frac{60V_{\min}}{\pi d}} = \frac{\pi n}{120V_{\min}}(Dd - d^2). \tag{4}$$

Maximizing T with respect to d,

$$\frac{\delta T}{\delta d} = \frac{\pi n}{120V_{\min}}(D - 2d) = 0$$

---

* Decimal classification: 621.385.971. Original manuscript received by the Institute, September 15, 1948; revised manuscript received, March 3, 1949.

† Columbia Broadcasting System, Inc., New York, N. Y.
‡ Columbia Records, Inc., New York, N. Y.

[1] Trade-mark of Columbia Records, Inc., New York, N. Y.

and

$$d = \frac{D}{2} \cdot \tag{5}$$

In other words, maximum playing time for a given inner-groove linear velocity is obtained when the inner diameter of the record equals one-half the outer diameter.

From (4), with $d = D/2$

$$T = \frac{\pi n D^2}{480 V_{\min}}$$

and

$$n = \frac{480 V_{\min} T}{\pi D^2} \cdot \tag{6}$$

Thus, when $T = 20$ minutes, $V_{\min} = 10$ inches per second and $D = 11.5$ inches; the number of grooves per inch n will be 230. As the nearest practical value, 224 grooves per inch are used for all records up to 20 minutes per side, or 40 minutes total playing time. This requires an inner diameter of 5.5 inches, with a corresponding velocity of 9.6 inches per second. On record sides requiring more than 20 minutes of playing time, 260 grooves per inch are used.

TRACING DISTORTION

Increasing the length of playing time by an appreciable factor was only one of the goals to be accomplished. With the advent of FM and professional tape recorders, improved performance over standard 78-rpm and even transcription records became a necessity.

In the following, an analysis will be made of the performance of Columbia's LP records in relation to commercial 78-rpm records, and also to transcription-type recording. The chief factors considered will be those which are influenced by the linear speed and by the amplitude excursions of the reproducing stylus. It has been found in disk recording in general that the limitations imposed by cutter performance, such as clearance angle of cutting stylus, acceleration of the stylus, etc., are usually less limiting than the tracing distortion, which is a function of the minimum radius of curvature of the traced waves and the effective radius of the reproducing stylus.[2]

First, the minimum radius of curvature corresponding to maximum deviation amplitude for various types of records (78-rpm, transcription, and LP) will be determined; at the same time, it will be postulated that the radius of curvature is not to be less than the effective radius of the reproducing stylus. This does not imply that such a condition ensures distortion-free reproduction, since, even under this condition, the center of the reproducing stylus does not trace a sine wave. Distortion increases very rapidly when the effective stylus radius exceeds the radius of curvature.[2] The purpose of this analysis, however, is to show the relative performances of 78-rpm, transcription, and LP records, rather than to define certain requirements already well-known in the recording field.

Arbitrarily, the condition where the two radii (namely, minimum radius of curvature of wave and effective radius of reproducing stylus) are equal, will be named the limiting condition, and the corresponding frequency will be termed the limiting frequency.

In general, the radius of curvature for a function $y = f(x)$ can be expressed as follows:

$$r = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\frac{d^2y}{dx^2}} \cdot \tag{7}$$

Applying this to a sine wave, $y = D \sin 2\pi x/\lambda$, it can be shown that r has a minimum for $x = \lambda/4$. Thus,

$$r_{\min} = \frac{\lambda^2}{4\pi^2 D} \cdot \tag{8}$$

The wavelength λ as traced on the record is equal to the linear velocity V of the groove at that point, divided by the frequency f of the energy delivered to the cutting stylus. Therefore, the frequency at which the minimum radius of curvature will equal the effective reproducing-stylus tip radius for the deviation D can be called limiting frequency, and will be

$$f_l = \frac{V}{2\pi\sqrt{r_{\mathrm{eff}} D}} \cdot \tag{9}$$

Actual values of f_l can now be determined for 78-rpm records, transcription disks, and LP records for the maximum possible deviation ($D_{\max}$) when using the innermost grooves. The critical frequency values are of greatest interest for those grooves nearest the center because of their low linear velocity.

For 78-rpm records at a 4-inch diameter, the linear velocity $V = 16.3$ inches per second. The tip radius is usually 3 mils, and the effective radius $r_{\mathrm{eff}} = 0.003 \cos \alpha/2$, where α is the total groove angle. Thus, since $\alpha = 90°$, $r_{\mathrm{eff}} = 0.0021$ inch. The peak displacement $D_{\max} = 0.002$ inch; substituting these values in (9),

$$f_{l(78)} = \frac{16.3}{2\pi\sqrt{(0.0021)\cdot(0.002)}} = 1{,}270 \text{ cps.} \tag{10}$$

The limiting frequency for transcription records is

$$f_{l(TR)} = \frac{14}{2\pi\sqrt{(0.0017)\cdot(0.0011)}} = 1{,}620 \text{ cps.} \tag{11}$$

---

[2] W. S. Bachman, "Phonograph dynamics," *Electronic Ind.*, vol. 4, pp. 86–89; July, 1945.

Finally, the innermost grooves of LP records have a inear velocity of the order of 9.6 inches per second; he reproducing-stylus tip radius is 0.001 inch, and the ffective radius equals 0.0007 inch. The maximum groove deviation is 0.0009 inch. From these values, it ollows that

$$f_{l(LP)} = \frac{9.6}{2\pi\sqrt{(0.0007)\cdot(0.0009)}} = 1{,}940 \text{ cps.} \qquad (12)$$

Thus, the limiting frequency for LP records is higher than for either transcription records or standard 78-rpm records.

With regard to these frequency values, an obvious conclusion would be that none of the three recording systems under scrutiny is capable of reproducing frequencies above the values corresponding to the limiting frequency; in the case of the LP record, this would be 1,940 cycles. It is necessary to keep in mind, however, that the various values for f were established using the maximum groove displacement $D_{\max}$.

Since second-harmonic distortion is automatically eliminated by virtue of the complete symmetry of the distortion produced in the traced waves, another way of comparing tracing distortion between 78-rpm commercial records, transcription records, and the LP microgroove records is to utilize an expression for the rms value of third-harmonic lateral tracing distortion[3] T.

$$T = \frac{6\pi^4 \cdot r^2 \cdot D^2 \cdot f^4}{V^4} \cos^2 \frac{\alpha}{2}, \qquad (13)$$

where

r = tip radius of the reproducing stylus in inches
D = peak amplitude of the recorded wave in inches
f = frequency of the recorded wave in cps
V = linear groove velocity in inches per second
α = groove angle.

Since the purpose is to determine the relative distortion of various disk-recording systems, a graph has been prepared (Fig. 1) in which, based on (13), the distortion of LP records, commercial transcription records, the recently announced RCA 7-inch record, and conventional 78-rpm records has been determined in relation to the tracing distortion on the inside of the standard 78-rpm disk. The ordinate gives the inverse of this distortion ratio, so that, the higher the ordinate value, the better the theoretical quality of the record. For instance, the LP record on the outside (zero minutes playing time) shows 85 times less distortion than the inside of the conventional 78-rpm record. After 21 minutes playing time, the LP record shows roughly 6.2 times less distortion. The RCA 7-inch record shows 7.4 times less distortion. With respect to actual demonstrable differences among these various types of records, it can be seen that the tracing distortion on the inside of commercial transcription records (after 15 minutes playing) is roughly one-third of that found on the inside of the 78-rpm record. It is questionable whether additional reduction in tracing distortion can be demonstrated with anything short of professional laboratory equipment when using regular program material.

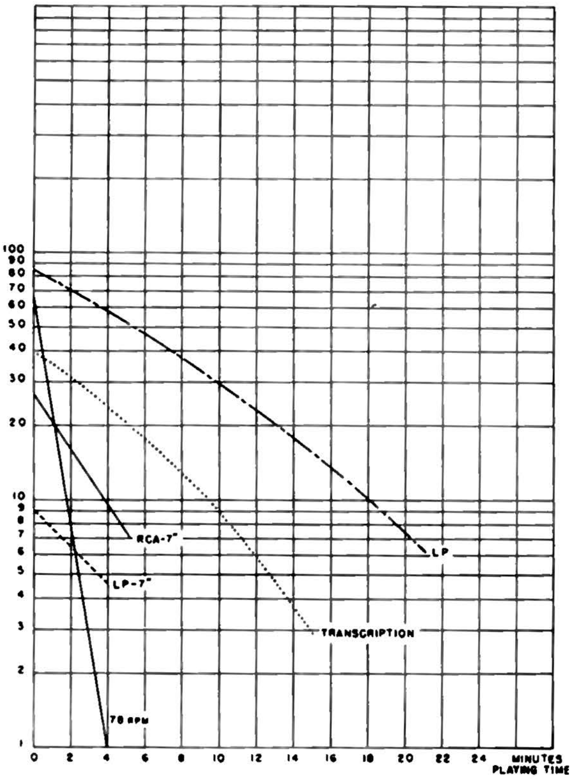

Fig. 1—Performance characteristics of various types of records.

Equation (9) may be written with $r_{\min} = r_{\text{eff}}$.

$$D_{\text{usable}} = \frac{V^2}{4\pi^2 f^2 r_{\text{eff}}}. \qquad (14)$$

This corresponds to the usable deviation that may be employed in recording a frequency f while still retaining the original condition that the stylus radius does not exceed the minimum radius of curvature of the recorded wave. From (14),

$$\frac{D_{\text{usable}}}{D_{\max}} = \frac{\dfrac{V^2}{4\pi^2 f^2 r_{\text{eff}}}}{\dfrac{V^2}{4\pi^2 f_l^2 r_{\text{eff}}}} = \left(\frac{f_l}{f}\right)^2. \qquad (15)$$

In Fig. 2, $D_{\text{usable}}/D_{\max}$ is plotted in percentage versus frequency for 78-rpm records, for transcription records, and for LP records. The ordinate indicates percentage usable maximum groove displacement where 100 per cent equals the maximum possible values used in (10),

---

[3] W. D. Lewis and F. V. Hunt, "A theory of tracing distortion in sound reproduction from phonograph records," *Jour. Acous. Soc. Amer.*, vol. 12, p. 353, 1941.

(11) and (12). Thus, 100 per cent modulation equals 0.002 inch (10) for 78-rpm records; 0.0011 inch (11) for transcription records; and 0.0009 inch (12) for LP records. As indicated previously, these conditions are those prevailing at the lowest linear velocity (inside grooves) for each particular type of record.

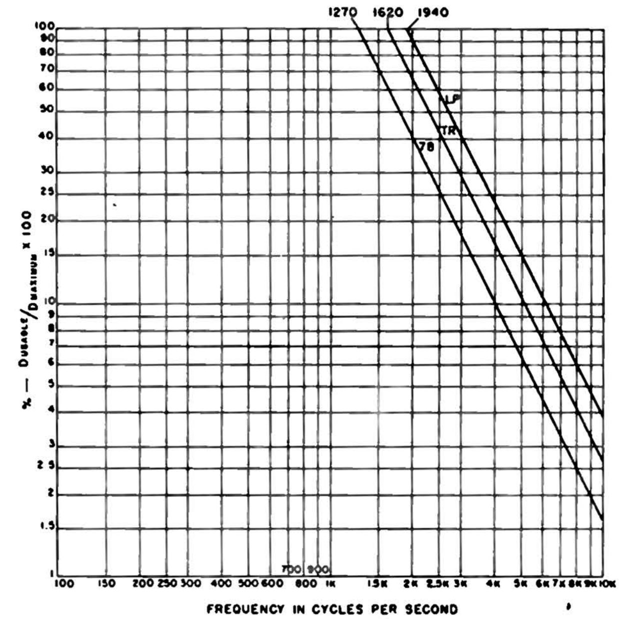

Fig. 2—Percentage maximum deviation versus frequency.

The LP recording characteristic (velocity versus frequency) is shown by curve 1 in Fig. 3. Curve 2 in Fig. 3 shows the NAB velocity recording characteristic, which deviates from the LP characteristic in the low bass portion only. The purpose for the LP bass lift is to reduce rumble and hum pickup, which would otherwise be more pronounced with the smaller deviations.

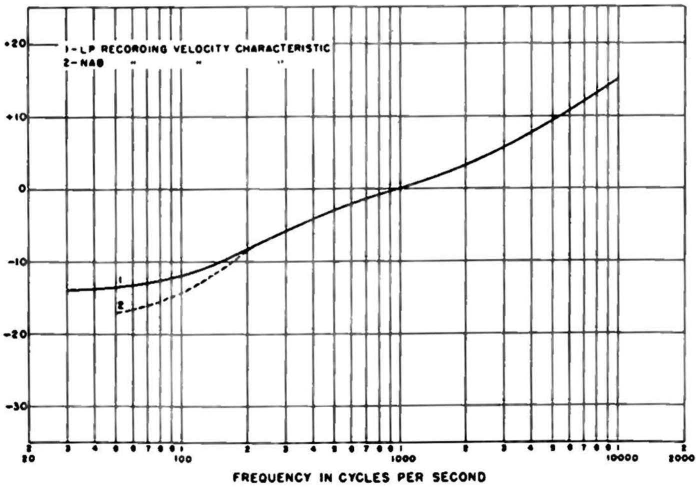

Fig. 3—LP and NAB recording characteristics.

Hand in hand with the LP record, suitable reproducing equipment has been developed in the Columbia Laboratories. Existing pickups, such as used for 78-rpm records, obviously could not be employed. First, as has been mentioned previously, the tip radius for LP records should be 0.001 inch (± 10 per cent). Second, the weight requirements are quite different. Extensive tests have shown that, for a stylus of 0.001-inch radius, as used with the LP records, a downward stylus force not exceeding 6 grams is desirable. An LP stylus employing a 6-gram force exerts no more pressure than the average 78-rpm pickup.

The necessity of developing a single cartridge capable of tracking both LP and 78-rpm records with only 6 grams stylus force was also realized. As a result, two cartridges with a new nonresonant type of arm were developed; a single cartridge playing LP records only, and another cartridge having two styli and a single crystal capable of playing either LP or 78-rpm records. Both cartridges track with a downward force of only 5 to 6 grams and have approximately 0.5 volt rms output. These cartridges, with an associated filter, have a substantially flat response over the entire recorded frequency range.

Since the included groove angle of both LP and 78-rpm records is approximately 90 degrees, the vertical force F_v tending to force the stylus out of the groove is equal to the total lateral force on the stylus F_L. This force has a component F_s which overcomes the stiffness of the stylus and tends to force the stylus away from its position of equilibrium, and an opposing component F_a, which accelerates the stylus toward its position of equilibrium. At low frequencies, where most tracking problems were encountered, F_a, which decreases with the square of the recorded frequency, becomes negligible compared to F_s, and can, therefore, usually be neglected.

Then,

$$F_v = F_L = F_s \text{ (at low frequencies).} \tag{16}$$

Now

$$F_s = \frac{D_{\max}}{C} \tag{17}$$

where C is the compliance measured at the point of the stylus.

From (16) and (17),

$$F_v = \frac{D_{\max}}{C} \quad \text{or} \quad C = \frac{D_{\max}}{F_v}. \tag{18}$$

Substituting the $D_{\max}$ and F_v used in the LP system in (18),

$$C = \frac{(0.0009)\cdot(2.54)}{(6)\cdot(980)} = (0.39)\cdot 10^{-6} \text{ cm/dyne.} \tag{19}$$

Substituting the corresponding values for the 78-rpm side of the dual cartridge,

$$C = \frac{(0.002)\cdot(2.54)}{(6)\cdot(980)} = (0.87)\cdot 10^{-6}\ \text{cm/dyne}. \qquad (20)$$

This higher value of compliance was obtained by employing a stylus wire of a smaller diameter. Actual compliance values in these cartridges are more than double the values given above, which represent the lowest ones required theoretically.

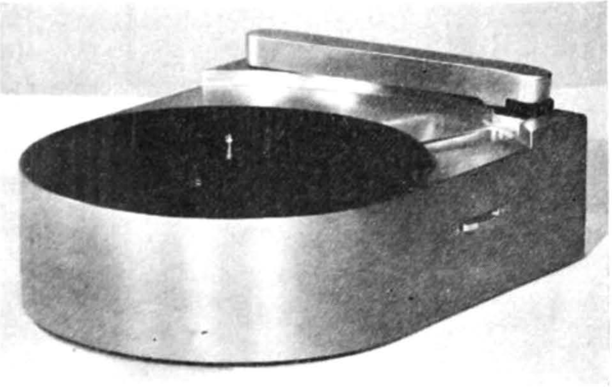

Fig. 4—Columbia's experimental dual cartridge-dual speed player.

Fig. 5—Philco LP record player.

A number of laboratory player attachments were built using the newly developed pickups and employing standard two-pole motors, modified to give wow- and rumble-free reproduction. The players and the records were field-tested in homes over a considerable period of time. Fig. 4 shows the LP attachment designed by Columbia to play both 78-rpm and LP records using the nonresonant arm and dual cartridge described previously. Fig. 5 shows the Columbia player attachment engineered by Philco.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to John W. Christensen, chief engineer of the CBS Engineering Research and Development Department, who contributed generously to the success of this project and to the preparation of this paper.

Credit and thanks are also due to Daniel Doncaster, Thomas Broderick, and Bertram Littlefield, of the CBS Laboratories, and Eric Porterfield, of the Columbia Records technical staff, who rendered much valuable assistance during the past three years.

Direct Voltage Performance Test for Capacitor Paper*

HAROLD A. SAUER† AND DAVID A. McLEAN†

Summary—Performance of capacitors on accelerated life test may vary over a wide range depending upon the capacitor paper used. Indeed, at present a life test appears to be the only practical means for evaluating capacitor paper, since, within the limits observed in commercial material, the chemical and physical tests usually made do not correlate with life. Lack of correlation is ascribed to obscure physical factors which have not yet been identified.

Generally, several weeks are required to evaluate a paper by life tests of the usual severity. Unfortunately, the duration of these tests is too long for quality control of paper.

The desire for a life test which requires no more than a day or two for evaluation led to the development of a rapid dc test. The philosophy of rapid life testing is based upon the experimental evidence that the process of deterioration under selected temperature and voltage conditions is principally of a chemical nature, and also upon the well-known fact that rates of chemical reaction increase exponentially with temperature.

Life tests on two-layer capacitors conducted at 130°C provide an acceleration in deterioration many fold more than that obtained in the lower-temperature life tests, and correlate well with these tests.

* Decimal classification: R281×R215.13. Original manuscript received by the Institute, June 7, 1948; revised manuscript received, November 24, 1948.

† Bell Telephone Laboratories, Murray Hill, N. J.