

MECHANICAL PHENOMENA IN GRAMOPHONE PICK-UPS AT HIGH AUDIO FREQUENCIES

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An article on a new gramophone pick-up will shortly appear in this review. As an introduction to this article we give here a study of the mechanics of the system pick-up - record, particularly at high audio frequencies. Extensive calculations on this question can be found in the literature; often, however, the physical aspect on the phenomena is liable to get lost and only after considerable simplification are useful results obtained. In this article the higher harmonics of the stylus motion are neglected at the outset, so that the mathematics does not cloud the general physical picture.

Two phenomena are important in determining the frequency response of a pick-up in the higher audio range (about 5000 to 20 000 c/s). The first is the stylus-groove resonance, i.e. the resonance of the effective mass, thought of as concentrated in the stylus tip, and the stiffness of the walls of the groove in which the stylus rests. The second phenomenon is the loss of high notes owing to the elastic deformation brought about by the stylus tip in the walls of the groove, a loss that is greater the smaller are the radii of curvature of the groove walls, i.e. the higher the modulation frequency, the greater the amplitude and the nearer the pick-up is to the centre of the disc.

The theory of the elastic deformation of two curved bodies in mutual contact under the influence of a given force as given by Hertz¹⁾ can be applied to both phenomena. As early as 1941 Kornei²⁾ developed a theory based on Hertz' work to explain the "playback loss" at higher frequencies.

On the basis outlined by Kornei, F. G. Miller³⁾ developed a broadly conceived theory on the relations between groove and stylus. Apart from the deformation of the groove walls, he includes the distortion in the motion of the stylus when tracing a groove with perfectly rigid walls, in which he employs the calculations of Lewis and Hunt⁴⁾. This tracing distortion arises from the finite dimensions of the stylus tip, so that the curve traced by the stylus is not entirely identical with that cut into the record. In this further analysis Miller splits

up the complex motion of a stylus riding a sinusoidal groove into a fundamental component and higher harmonics; as regards the fundamental component he arrives at relatively simple formulae, from which are derived the phenomenon of stylus-groove resonance as well as the loss of high notes.

In order to gain a clearer picture of the physical phenomena, the higher harmonics will be disregarded here. We can thus confine ourselves to a greatly simplified derivation, keeping in mind, however, that this theory will not be entirely valid in extreme cases such as may occur sometimes in practice. This simplification also means that wherever we speak of deformations, these are considered to be of a purely elastic nature, according to Hooke's law. The highly complex phenomena occurring with plastic deformation do not lend themselves to a simple description⁵⁾.

In the following considerations of the pick-up as a mechanical system only the trajectory of the stylus tip will be studied; resonances of the mechanical transmission system and of the electrical circuit will be disregarded.

Deformation of the groove walls

Before dealing with the deformation of the groove walls by the reproducing stylus, let us first consider the geometry of the groove and the forces exerted by the stylus on the groove walls. Let us assume that a sinusoidal signal

$$y = \hat{y} \sin \omega t$$

has been recorded, the y -axis being chosen in the plane of the record, normal to the unmodulated groove. During playback the angular frequency is determined by the "wavelength" λ registered in

¹⁾ Heinrich Hertz, *Gesammelte Werke*, III. Die Prinzipien der Mechanik. J. A. Barth, Leipzig 1894; S. Timoshenko, *Theory of elasticity*, McGraw-Hill, New York 1934.

²⁾ O. Kornei, On the playback loss in the reproduction of phonograph records, *J. Soc. Mot. Pict. Engrs.* 37, 569-590, 1941.

³⁾ F. G. Miller, Stylus-groove relations in phonograph records, dissertation, Harvard 1950.

⁴⁾ W. D. Lewis and F. V. Hunt, *J. Acoust. Soc. Amer.* 12, 348-356, 1940/41. See also: J. A. Pierce and F. V. Hunt, *J. Acoust. Soc. Amer.* 10, 14-28, 1938/39.

⁵⁾ F. V. Hunt, On stylus wear and surface noise in phonograph playback systems, *J. Audio Eng. Soc.* 3, 2-18, Jan. 1955.

the record, and by the linear velocity V_g of the groove, according to:

$$\omega = 2\pi \frac{V_g}{\lambda} \quad (1)$$

Fig. 1 shows part of such a sinusoidal groove; the stylus tip, represented by a sphere, is situated here just at the crest of the wave. At this spot both lateral amplitude and acceleration are greatest, so

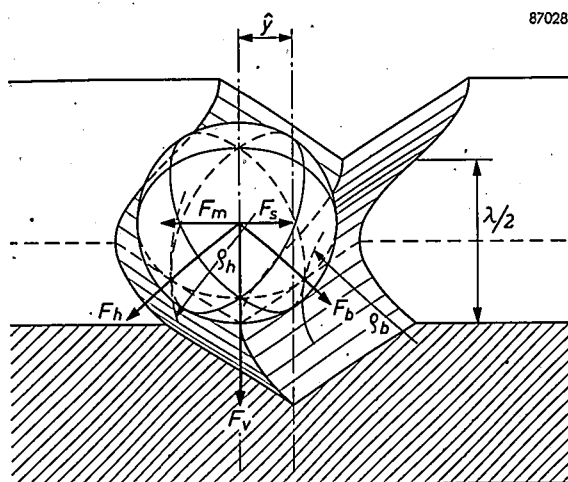


Fig. 1. The stylus tip, represented as a sphere, rests in the groove of a record, near the crest of the recorded sine wave. The walls of the groove are thought of as perfectly rigid.

that both stiffness force and inertia force will also be maximum. These forces can be represented respectively by

$$\hat{F}_s = s\hat{y}_a \quad \text{and} \quad \hat{F}_m = m\omega^2\hat{y}_a \quad (2)$$

s being the stiffness and m the effective mass of the stylus system considered as acting through the centre of the stylus tip; \hat{y}_a is the amplitude of the actual stylus trajectory, which will generally differ from y , as will be shown later (suffix a for "actual", because the curve representing \hat{y}_a as a function of the frequency will be called the actual pick-up characteristic; see below). $F_s - F_m$ is the nett lateral force F_l on the stylus tip.

Apart from this lateral force, a vertical force F_v acts on the stylus tip. If we disregard the "pinch" effect⁶⁾ the latter force can be considered as constant.

In the foregoing no mention has been made of the damping of the pick-up. In general, F_l may be written as⁷⁾:

$$F_l = \left(\frac{s}{j\omega} + r + j\omega m \right) v \quad (3a)$$

$$F_l = \left(s + r \frac{d}{dt} + m \frac{d^2}{dt^2} \right) y_a \quad (3)$$

where r represents the damping of the pick-up. In fig. 2 the two forces F_l and F_v are represented again, with their components at right angles to the groove walls.

The groove angle 2β , being very nearly 90° in practice, is assumed, for the sake of simplicity, to be exactly 90° . For the forces normal to the groove walls we then obtain⁸⁾

$$F_h = \frac{1}{2}\sqrt{2} (F_v + F_l) \quad (4)$$

$$F_b = \frac{1}{2}\sqrt{2} (F_v - F_l)$$

where the suffix h refers to the concave side of the groove and b to the convex side. These forces cause elastic deformations of the groove walls. The depth of the deformations is determined not only by these forces, but also by the nature of the materials and by the curvatures of the surfaces concerned. Evidently, a stylus tip with a small radius of curvature will penetrate deeper into the groove wall than one with a larger radius. It is likewise fairly obvious that a stylus tip of given radius will penetrate deeper into the convex than into the concave wall of the groove, since the contact area of the stylus with the latter is greater.

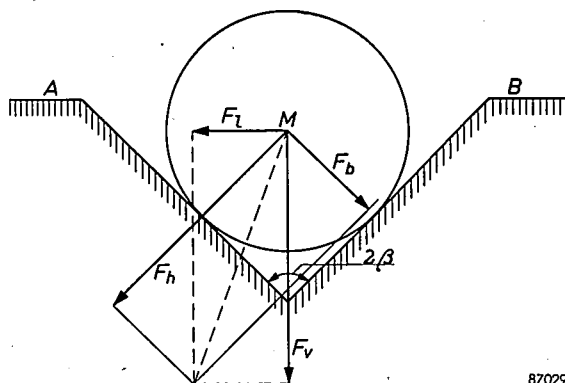


Fig. 2. Cross-section through the centre M of the stylus tip, for the situation shown in fig. 1. The groove-wall is concave at A , convex at B .

All this can be expressed in a formula given by Hertz for the elastic deformation of curved bodies in contact under a given force. For this special case the formula takes the form:

$$a = \left\{ \left(\frac{3}{2} \right)^2 F^2 \left(\frac{1 - \sigma^2}{E} \right)^2 \frac{1}{R} \left(1 \pm \frac{R}{2q} \right) \right\}^{\frac{1}{3}} \quad (5)$$

⁸⁾ In fig. 2 the direction of F_l is to the left. This direction depends not only on the relative magnitude of F_s and F_m (the latter a function of frequency) but also on the damping, which introduces a phase angle between F_l and F_m . The effects of these quantities on the direction of F_l may be quantitatively examined by considering the mechanical impedance and the velocity as functions of the frequency; cf. eq. (3a) in footnote 7).

⁶⁾ See e.g. Philips tech. Rev. 13, 139, 1951/52.

⁷⁾ If the method of complex numbers is used, F_l may also be expressed as the product of the mechanical impedance at the stylus tip and the velocity $v = j\omega y_a$:

The symbol a represents the depth of penetration, F the force exerted by the stylus normal to the groove wall, E and σ respectively the Young's modulus and the Poisson's ratio of the record material (for both shellac and plastic records, $\sigma \approx 0.35$), R the radius of the spherical tip of the stylus, and ρ the radius of curvature of the groove wall in a plane subtending an angle β with the horizontal plane. In (5) the plus-sign applies to a convex groove wall, the minus-sign to a concave one.

In Hertz's original formula a term appears with Young's modulus of the stylus material (at present generally sapphire or diamond) in the denominator. This modulus, however, is so much greater than that of the record material that this term can be neglected; in comparison with the record, the stylus can be regarded as perfectly rigid. The relevant values of E are roughly as follows ⁹⁾:

Material	E (newtons/m ²)
Plastic	3×10^9
Shellac	6×10^9
Sapphire	500×10^9
Diamond	900×10^9

(The plastic referred to here is a copolymer of vinyl chloride and vinyl acetate ¹⁰⁾, commonly used for long-playing records.)

Substituting the values of F given by (4) in (5) and grouping the constants together, we obtain for the penetration depths a_b and a_h in the convex and the concave side respectively:

$$a_{b,h} = \left\{ \left(\frac{3}{4} \right)^2 \left(\frac{F_v}{2} \right)^2 \left(\frac{1-\sigma^2}{E} \right)^{\frac{2}{3}} \frac{1}{R} \right\}^{\frac{1}{3}} \left\{ 1 \mp \frac{F_l}{F_v} \right\}^{\frac{2}{3}} \left\{ 1 \pm \frac{R}{2\rho} \right\} =$$

$$= a_0 \left\{ 1 \mp \frac{F_l}{F_v} \right\}^{\frac{2}{3}} \left\{ 1 \pm \frac{R}{2\rho} \right\}, \quad \dots \quad (6)$$

where a_0 represents the penetration depth in an unmodulated groove, since in this case $F_l = 0$ and $\rho = \infty$.

It follows from (6) that the penetration depths can be reduced by increasing E (in this respect shellac is to be preferred to plastic), by increasing R , or by reducing F_v . Later in this article we shall consider the effect of F_l and ρ .

Fig. 3 shows a cross section of a stylus in an unmodulated groove indicating a typical static deformation. The value of a was derived from the values of F_v , E , λ and R . Fig. 4 is a perspective sketch of a stylus resting (stationary) in a modulated groove.

Analysis of the stylus motion

The trajectory of the stylus can be studied with the aid of the following imaginary experiment. The pick-up rests in a stationary groove, e.g. at the crest of a sine wave, as shown in fig. 1. Because the penetration in the convex groove wall is deeper than in the concave one, the tracing sphere rests such that the horizontal distance of its centre from the zero line (centre of unmodulated groove) is not \hat{y} , as would be the case with a perfectly rigid wall (fig. 5a) but smaller, say \hat{y}_s (s for the static situation considered) as in fig. 5b. If the stylus is exactly at the point where the groove passes through zero, the penetrations on either side will be equal, as the groove can be considered straight at this point. In this case, therefore, the horizontal projection of the centre coincides with the point of zero amplitude (N in fig. 5b).

Progressing accordingly for intermediate points, we arrive at a curve such as y_s in fig. 5b. A loss in

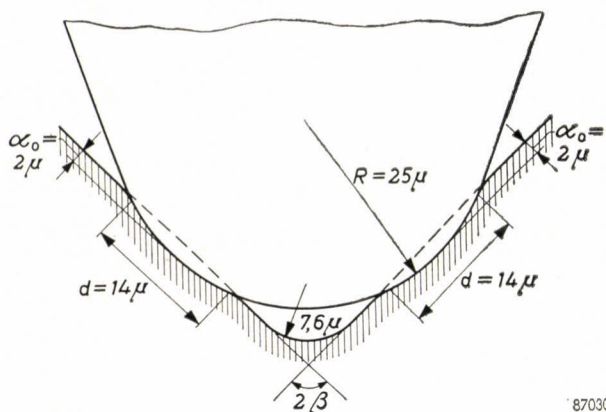


Fig. 3. Elastic penetration by the stylus in the walls of an unmodulated groove, drawn to scale for a co-polymer plastic record with $E = 3.3 \times 10^9$ N/m² and $\sigma = 0.35$. Groove angle $2\beta = 90^\circ$. Apex angle of stylus 45° . Vertical force $F_v = 0.1$ N (≈ 10 g). Depth a_0 of the penetration is 2μ , diameter d of contact area is 14μ .

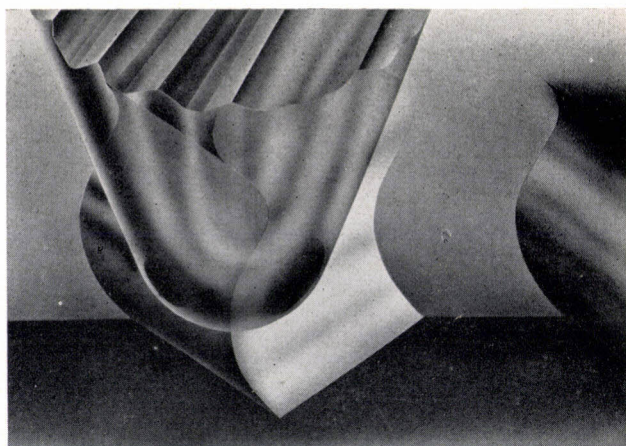


Fig. 4. Perspective drawing, showing the static situation with the stylus resting in a modulated groove.

⁹⁾ Values in M.K.S. units. The newton is the force necessary to produce an acceleration of 1 m/sec² in a mass of 1 kg, i.e. the force exerted by the weight of 1/g kg, where $g = 9.81$ m/sec²; this gives 1 N $\approx 1/10$ kg weight. Hence to convert the values given to kg/mm² they should be multiplied by 10^{-7} .

¹⁰⁾ See Philips tech. Rev. 17, 108, 1955/56 (No. 4).

amplitude will be noted; this will be termed the *static tracing loss*. The amplitude $\hat{\delta}_s$ of this loss is $\hat{y} - \hat{y}_s$.

As long as the record is stationary we are only concerned with a constant vertical force due to the stylus pressure, which can be resolved into two components normal to the groove walls. Although these components are equal in magnitude, it is owing to the opposite curvatures of the walls that they cause impressions of different shapes (O_1 and O_2 in fig. 5b). When the record is turning, additional lateral forces come into play. Let us assume that a sinusoidal signal of constant wavelength is recorded

force is then exerted on the stylus. Hence δ_d becomes zero; the total loss is then equal to the static tracing loss. The frequency at which this happens is called the resonance frequency of the pick-up system. Since the external lateral force on the stylus is now zero, this resonance of the effective mass at the stylus tip and the stiffness of the pick-up system is the same as would occur with the stylus freely vibrating in air, outside a groove.

From $F_m = F_s$, the free resonant frequency is given (see eq. 2) by $s\hat{y}_a = m\omega^2\hat{y}_a$, or $\omega = \sqrt{s/m}$. This resonance does not appear in the actual

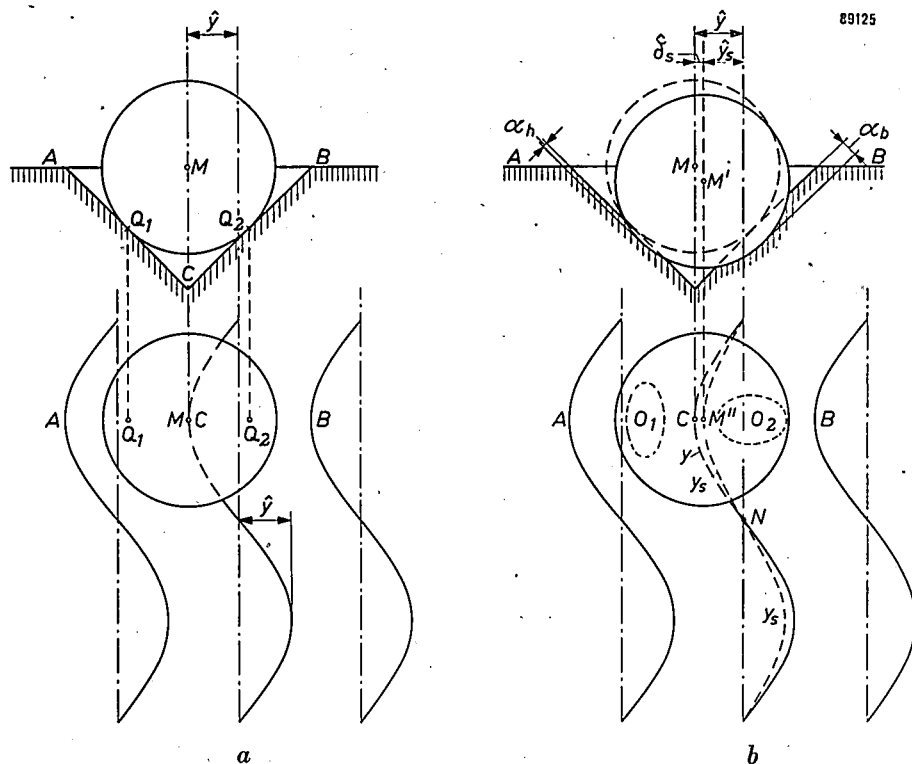


Fig. 5. a) Stylus in groove with perfectly rigid walls. Stylus and groove touch at only two points, Q_1 and Q_2 ; no horizontal displacement of the centre M of the stylus tip. b) Same for a groove with elastic walls. The points of contact of stylus and groove have now become areas (O_1 and O_2 shown exaggerated for clarity); the penetration α_b at the convex side of the groove (B) is deeper than α_a , and consequently M is shifted to M' over a distance whose horizontal projection CM'' is $\delta_s = \hat{y} - \hat{y}_s$ in the event that the stylus is situated at the crest of the sine. Instead of the recorded sine curve y , the stylus describes the curve y_s of smaller amplitude.

and that the record is now slowly started and gradually speeded up. According to equation (1) the frequency will then gradually increase. As long as the frequency is low, the stiffness force F_s will exceed the inertia force F_m and, apart from the earlier mentioned tracing loss, a *dynamic tracing loss* δ_d will occur. The total tracing loss δ_t is the sum of δ_d and δ_s .

As the frequency becomes higher, F_m increases until at a certain frequency F_m is just equal to the force F_s provided by the stiffness: no external lateral

pick-up characteristic; it occurs, for most pick-ups, at a frequency between about 1000 and 2000 c/s, which is considerably below the *stylus-groove* resonance (to be dealt with later) which has the major effect on the actual characteristic.

At frequencies above the resonance frequency of the pick-up system the force F_m will predominate and the dynamic tracing loss δ_d will thus become negative, i.e. the total tracing loss will be less than the static loss. At a sufficiently high F_m (hence high frequency and/or large mass) the total loss

may even become negative, and there will therefore be some amplification of the signal. The amplification is greatest at the frequency at which the stylus-groove resonance (stylus-tip inertia and groove-wall stiffness) takes place. This resonance depends on the material of record and stylus, on the shape of groove and stylus and further on the vertical force.

Summarizing, we find that when an ordinary record (unlike our theoretical model modulated with varying wavelength) is played back two opposite effects occur: at higher frequencies the radii of curvature are smaller and therefore the static loss is large, while at the same time the inertia forces increase and thus the dynamic loss is reduced. (This is directly apparent from the signs in (6)). Which of the two effects is predominant depends upon several factors and will be discussed at the conclusion of this article, after dealing with each effect separately.

Static tracing loss and cut-off frequency

The static tracing loss was defined in the foregoing by $\delta_s = y - y_s$, where y represents the signal registered in the record and y_s the lateral deflection of the stylus tip. The static tracing loss increases according as the radius of curvature of the groove walls becomes smaller. At a given radius (and when the amplitude \ll radius of stylus point, as it always is for the frequencies under consideration), the loss can even equal the original signal: $y = \delta_s$. Then $y_s = 0$; in other words, the stylus describes an unmodulated trajectory and the pick-up does not produce any voltage. We shall evaluate this case for the peak of a sine wave; at this point the deformation is largest and the calculation is simplest.

The following relation exists between the absolute value $|e|$ of the radius of curvature at the peaks and the wavelength or frequency:

$$|e| = \frac{V_g^2 \sqrt{2}}{\hat{y} \omega^2} = \frac{\lambda^2 \sqrt{2}}{4\pi^2 \hat{y}} \quad (7)$$

where V_g is the velocity of the stylus relative to the unmodulated groove.

The general expression for the radius of curvature of a curve, in Cartesian coordinates, is

$$e = \frac{\left\{ 1 + \left(\frac{dy}{dx} \right)^2 \right\}^{\frac{3}{2}}}{\frac{d^2y}{dx^2}}$$

In the present problem, the x coordinate is the direction of the unmodulated groove and the y coordinate is the displacement of the stylus from this axis. At a wave peak

$dy/dx = 0$, hence

$$e = \frac{1}{d^2y/dx^2}.$$

Since $y = \hat{y} \sin \omega t = \hat{y} \sin (\omega x/V_g)$, we have, at the peaks, $d^2y/dx^2 = -\hat{y} \omega^2/V_g^2 = -4\pi^2 \hat{y}/\lambda^2$. The factor $1/2$ is introduced in (7) because the radius of curvature considered is in a plane at an angle of 45° with the horizontal plane.

The frequency and wavelength corresponding to the radius of curvature at which the stylus no longer moves laterally, and at which the loss is therefore just as large as the original signal recorded, are called the *cut-off frequency* and the *cut-off wavelength*. At the cut-off frequency, F_1 is zero, since the lateral deflection is zero (cf. eq. (3)). However, we shall assume here that F_1 is zero throughout the whole frequency range in order to distinguish the static tracing loss from phenomena due to the action of an additional lateral force associated with the dynamic tracing loss. The formulae (6) for the penetration can then be expressed in the following simplified form:

$$\text{Convex side:} \quad a_b = a_0 \left(1 + \frac{R}{2\rho} \right)^{\frac{1}{2}},$$

$$\text{Concave side:} \quad a_h = a_0 \left(1 - \frac{R}{2\rho} \right)^{\frac{1}{2}}.$$

Now, by geometry,

$$\hat{\delta}_s = \frac{a_b - a_h}{2}.$$

Expanding the above expressions for a_b and a_h (neglecting higher powers of $R/2\rho$) and substituting we get

$$\hat{\delta}_s \approx \frac{a_0}{\sqrt{2}} \times \frac{2}{3} \frac{R}{2\rho}.$$

Using (7) this becomes

$$\hat{\delta}_s = \frac{a_0 R}{6 V_g^2} \omega^2 \hat{y}.$$

Hence

$$\hat{y}_s = \hat{y} - \hat{\delta}_s = \hat{y} \left(1 - \frac{a_0 R}{6 V_g^2} \omega^2 \right). \quad (8)$$

The cut-off frequency $f_{co} = \omega_{co}/2\pi$ and the cut-off wavelength λ_{co} are the values at which \hat{y}_s is zero, and hence

$$\omega_{co} = V_g \sqrt{\frac{6}{a_0 R}} \quad \text{and} \quad \lambda_{co} = \frac{2\pi V_g}{\omega_{co}} = 2\pi \sqrt{\frac{a_0 R}{6}}. \quad (9)$$

We now obtain for \hat{y}_s the following quadratic expressions in terms of ω/ω_{co} and of λ_{co}/λ :

$$\hat{y}_s = \hat{y} \left\{ 1 - \left(\frac{\omega}{\omega_{co}} \right)^2 \right\} = \hat{y} \left\{ 1 - \left(\frac{\lambda_{co}}{\lambda} \right)^2 \right\}. \quad (10)$$

The former expression is plotted in *fig. 6* (on logarithmic scale).

Since ω and ω_{co} are equally dependent upon the groove velocity V_g (equ. (1) and (9)), the effect of this velocity is not expressed in *fig. 6*. The fact that this effect is considerable can be readily demonstrated with the aid of a numerical example. Let us assume that $F_v = 0.1$ N (≈ 10 grams), $E = 3.3 \times 10^9$ N/m², $\sigma = 0.35$ and $R = 25 \times 10^{-6}$ m; we then find from (6): $a_0 = 2 \times 10^{-6}$ m. The cut-off wavelength is then $\lambda_{co} = 2\pi\sqrt{a_0 R/6} = 18\mu$, and hence the cut-off frequency is

$$f_{co} = V_g/\lambda_{co} = 55\,000 V_g \text{ c/s}, \quad (11)$$

V_g being expressed in metres per second. On the outside of a $33\frac{1}{3}$ r.p.m. 12" record, $V_g = 0.50$ m/s and f_{co} is consequently 27 500 c/s; on the inside, however, $V_g = 0.20$ m/s and f_{co} therefore only 11 000 c/s. Under such conditions, therefore, reproduction above 11 000 c/s is impossible near the

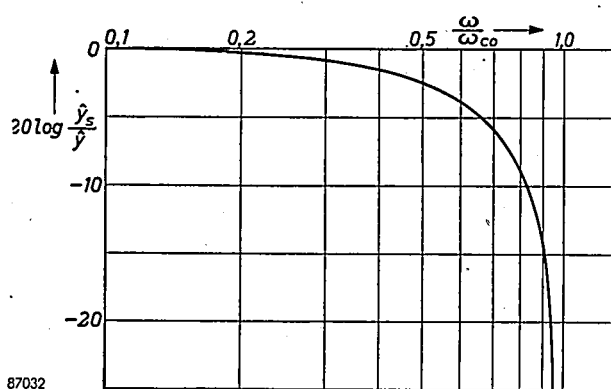


Fig. 6. The ratio $\hat{y}_s/\hat{y} = 1 - (\omega/\omega_{co})^2$ as a function of ω/ω_{co} (static characteristic, cf. *fig. 10*); both are plotted on logarithmic scales.

end of the record, and considerable attenuation occurs even below 11 000 c/s. (This attenuation is more or less compensated when the dynamic tracing loss becomes negative, but it is impossible to profit by this effect above the cut-off frequency).

In *fig. 7*, $20 \log \hat{y}_s/\hat{y}$ is plotted as a function of the groove velocity of a $33\frac{1}{3}$ r.p.m. record under the above-mentioned conditions, for various frequencies (eq. 8). It can be seen that the reproduction of the high notes is decidedly poorer on the inside than on the outside of the record.

Dynamic pick-up characteristic, dynamic tracing loss and resonance frequency

The dynamic pick-up characteristic is the characteristic after elimination of the static tracing loss dealt with in the foregoing (thus including the dynamic tracing loss).

The dynamic pick-up characteristic can be derived in a simple way by means of an electromechanical analogy¹¹). *Fig. 8a* is the equivalent diagram of the mechanical system. The signal $\hat{y} \sin \omega t$ is transferred via the elastic groove wall of stiffness S to the effective mass m concentrated in the stylus tip, the deflection y_d (suffix d for dynamic) of which we wish to find. The stiffness and the damping of the pick-up are denoted by s and r respectively.

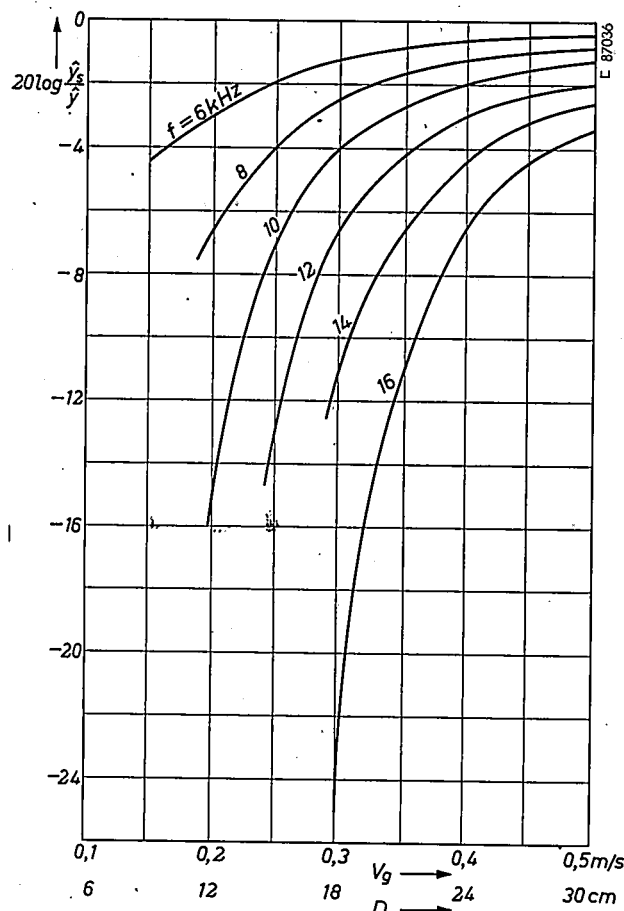


Fig. 7. \hat{y}_s/\hat{y} plotted logarithmically as a function of the groove velocity V_g , for a $33\frac{1}{3}$ r.p.m. record, for various frequencies f . For a given r.p.m., V_g is proportional to the distance of the groove from the axis of rotation, i.e. to the groove diameter D . The ordinate is therefore also expressed in terms of D .

The electrical analogue of this system is shown in *fig. 8b*. The motion of the stylus tip can easily be evaluated from this diagram. We find:

$$\hat{y}_d = \frac{\hat{y}}{\sqrt{\left(1 + \frac{s - m\omega^2}{S}\right)^2 + \left(\frac{r\omega}{S}\right)^2}} \quad (12)$$

¹¹) For the explanation and the application of electromechanical analogies, reference is made to the exhaustive literature on this subject, of which we particularly recommend: B. Gehlshøj, *Electro-mechanical and electro-acoustical analogies*, Ingenørvidenskabelige Skrifter (no. 1), Akad. tekn. Videnskaber, Copenhagen 1947.

By introducing the natural angular frequency of the stylus-groove system we obtain:

$$\omega_0^2 = \frac{S + s}{m} \quad (13)$$

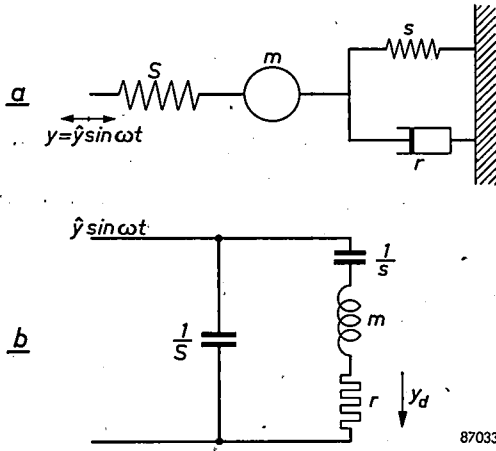


Fig. 8. a) Model of the pick-up mechanical system. m effective mass and s stiffness at the stylus tip, r damping, S stiffness of the groove wall. y_d is the displacement of the stylus tip resulting from an input signal y . b) Electrical analogue of (a).

Remembering that s is many times smaller than S ¹²), so that $\omega_0^2 \approx S/m$, and defining the relative damping coefficient as

$$\varepsilon = \frac{r}{m\omega_0},$$

we can finally put:

$$\hat{y}_d = \frac{\hat{y}}{\sqrt{\left\{1 - \left(\frac{\omega}{\omega_0}\right)^2\right\}^2 + \varepsilon^2 \left(\frac{\omega}{\omega_0}\right)^2}} \quad (14)$$

This formula represents the dynamic pick-up characteristic. The variation of \hat{y}_d as a function of the frequency for various values of the damping is shown in fig. 9.

The frequency at which \hat{y}_d assumes the maximum value is the stylus-groove resonance frequency $f_{res} = \omega_{res}/2\pi$. By putting $d\hat{y}_d/d\omega = 0$, we find

$$\omega_{res}^2 = \omega_0^2 (1 - \frac{1}{2}\varepsilon^2) = \omega_0^2 - \frac{r^2}{2m^2}.$$

The fact that the resonance frequency is lower than the natural frequency is due to the presence of damping; if the damping is small, however, the difference is negligible.

In the foregoing we have introduced the stiffness S of the groove walls. The value of S can be easily

related to F_v and α_0 if we take a simplified case¹³). If the stylus rode in an unmodulated groove and was driven by an external lateral force F_l , the depths of penetration would be given by a simplified form of (6) since $\rho = \infty$, i.e:

$$a_{b,h} = \alpha_0 \left(1 \mp \frac{F_l}{F_v}\right)^{\frac{2}{3}}.$$

The difference between the recorded and the traced signal, $y - y_d$ is what we have called in the foregoing the dynamic tracing loss δ_d ; $y_d = y - \delta_d$ is just a simplified expression of (12). The magnitude of the loss δ_d is given by expanding the above expressions for a_b and a_h (neglecting higher powers of F_l/F_v), subtracting and dividing by $\sqrt{2}$:

$$\delta_d = \frac{a_b - a_h}{\sqrt{2}} \approx \frac{\alpha_0}{\sqrt{2}} \times \frac{4}{3} \frac{F_l}{F_v}.$$

The groove wall stiffness S is defined as the ratio of the force F_l to the deflection δ_d due to that force in the presence of the vertical force F_v . Hence

$$S = \frac{F_l}{\delta_d} = \frac{F_l}{\frac{\alpha_0}{\sqrt{2}} \frac{4}{3} \frac{F_l}{F_v}} = \frac{3}{2} \frac{F_v}{\alpha_0 \sqrt{2}} \quad (15)$$

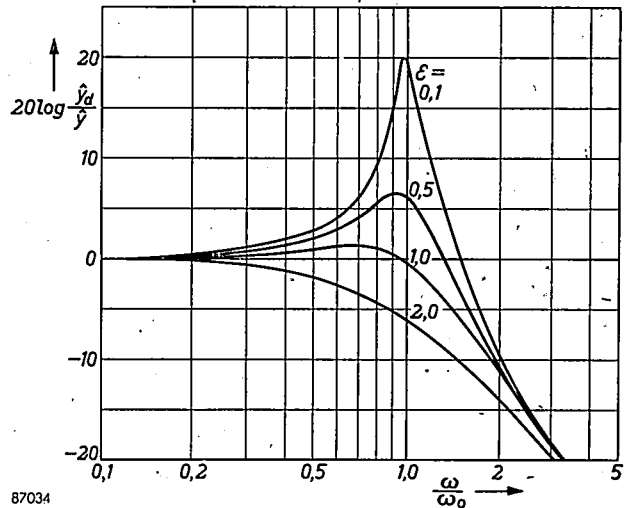


Fig. 9. Dynamic pick-up characteristic $\hat{y}_d = f(\omega/\omega_0)$, for various values of the relative damping coefficient ε (see eq. (14)). Provided that ε is not too large a peak occurs at a frequency (the stylus-groove resonance frequency) which lies further below the stylus-groove natural frequency $\omega_0/2\pi$ the stronger the damping. Both scales are logarithmic.

The actual pick-up characteristic

The actual pick-up characteristic gives the actual stylus trajectory \hat{y}_a as a function of the frequency. It consists of a combination of the dynamic pick-up characteristic and the static tracing loss.

¹²) For ordinary pick-ups, $s = 0.02$ to 1 kN/m, and for the groove wall $S = 40$ to 80 kN/m (depending on the material used, on the vertical force F_v and on the radius R of the stylus tip).

¹³) It can be shown mathematically that the result obtained here is equivalent to that obtained when the actual conditions are taken into account.

The equation of the actual characteristic can be derived as follows. Consider once again the expression (14) for the dynamic characteristic, keeping in mind that the static loss should, in fact, also be taken into account, so that in (14) \hat{y} should be replaced by \hat{y}_s , i.e.

$$\hat{y}_a = \frac{\hat{y}_s}{\hat{y}} \cdot \hat{y}_d.$$

Dividing this by \hat{y} and taking logarithms, we obtain:

$$\log \frac{\hat{y}_a}{\hat{y}} = \log \frac{\hat{y}_s}{\hat{y}} + \log \frac{\hat{y}_d}{\hat{y}}. \quad (16)$$

Hence if the static and the dynamic characteristics are plotted logarithmically on the same frequency scale, we obtain, as is evident from (16), the actual characteristic by adding the two functions. Alternatively, using the expression $y_d = y - \delta_d$, we can obtain the actual characteristic in an analogous manner by substituting in it $y - \delta_s$ for y . The result is then:

$$y_a = y - \delta_s - \delta_d = y - (\delta_s + \delta_d) = y - \delta_t,$$

where δ_t is the total loss.

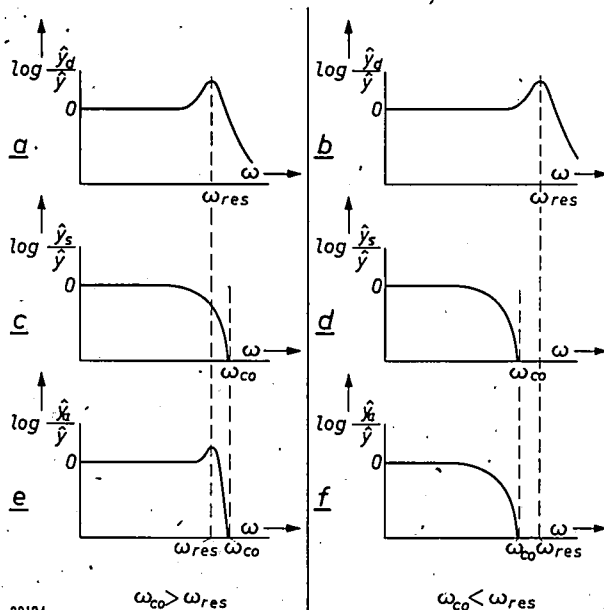


Fig. 10. (a) and (b) dynamic characteristic $\log \hat{y}_d/\hat{y}$, (c) and (d) static characteristic $\log \hat{y}_s/\hat{y}$, and (e) and (f) actual characteristics $\log \hat{y}_a/\hat{y} = \log \hat{y}_d/\hat{y} + \log \hat{y}_s/\hat{y}$; (a), (c) and (e) refer to $\omega_{c0} > \omega_{res}$; (b), (d) and (f) refer to $\omega_{c0} < \omega_{res}$.

$\log \hat{y}_d/\hat{y}$, $\log \hat{y}_s/\hat{y}$ and their sum $\log \hat{y}_a/\hat{y}$, are plotted in fig. 10, on the left for the case of $\omega_{c0} > \omega_{res}$, and on the right for $\omega_{c0} < \omega_{res}$.

In the former case the drop due to the static loss below the resonance frequency is reduced by the resonance peak in \hat{y}_d ; there remains a resonance

peak in \hat{y}_a , although less pronounced than in \hat{y}_d , whilst the region beyond the resonance frequency the cut-off is now sharper. In the second case ($\omega_{c0} < \omega_{res}$) the actual characteristic is virtually identical with the static one.

The practical importance of the various properties of pick-up and record

Consider the resonant angular frequency ω_0 of the stylus-groove system and the cut-off wavelength λ_0 . For the former quantity we take (13) in the approximate form $\omega_0^2 \approx S/m$, substitute for S from (15) and then insert the value of α_0 defined by equation (6). For λ_{c0} , we simply insert the value of α_0 from (6) in equation (9). We then obtain:

$$\omega_0 = \left\{ \frac{6}{\sqrt{2}} \frac{F_v R}{m^3} \frac{E^2}{(1-\sigma^2)^2} \right\}^{\frac{1}{6}}, \quad (17a)$$

$$\lambda_{c0} = \left\{ \frac{\pi^3}{\sqrt{12}} F_v R \frac{1-\sigma^2}{E} \right\}^{\frac{1}{3}}. \quad (17b)$$

ω_0 and λ_{c0} are quantities dependent only on the physical properties of the pick-up, the properties of the record material, and the vertical force F_v . They are therefore independent of the groove velocity and of the amplitude of the signal. For a given pick-up and a given record, ω_0 and λ_{c0} are to be regarded as system constants, which can be varied only by changing F_v . The cut-off frequency, however, as we have shown earlier, is determined by the relation $\omega_{c0} = 2\pi V_g/\lambda_{c0}$ and is consequently directly proportional to the groove velocity: ω_{c0} will thus be higher on the outside than on the inside of the record. The position of the stylus on the record will therefore be one of the factors deciding whether ω_{c0} is greater or smaller than ω_{res} (in most cases ω_{res} is virtually equal to ω_0). From the above the following conclusions may be drawn:

- 1) A reduction of the effective mass m at the stylus tip has no effect on λ_{c0} but it does raise the natural frequency ω_0 and consequently improves the reproduction of the high notes, provided that $\omega_0 < \omega_{c0}$.
- 2) The stiffness of the pick-up does not appear in (17a or b) and therefore affects neither λ_{c0} nor ω_0 . This is valid only for the high frequencies discussed here; s is obviously of importance at the lower frequencies.
- 3) The damping r of the pick-up determines the height of the resonance peak; it does so, however, in conjunction with the damping of the record material. The latter factor does not appear in the above considerations owing to the simplification introduced.

- 4) Increasing the Young's modulus E of the record material produces an increase in ω_0 and a reduction of λ_{co} . As mentioned in connection with the groove deformation, a shellac record, whose Young's modulus is about twice that of a plastic record, will be more favourable in this respect. Owing to other factors, however, such as the reduced noise and the unbreakability, the plastic material is nevertheless to be preferred (cf. the articles quoted in ⁹⁾ and ¹⁰⁾).
- 5) The radius of curvature R of the stylus tip is 25μ for long-playing records and 75μ for normal (78 r.p.m.) records. This greater radius causes a higher ω_0 but also a greater λ_{co} and, therefore, a greater static tracing loss if the same record material is used. Normal records, however, are usually made of shellac, which, as mentioned in 4) above, has a greater Young's modulus than plastic, and this partly compensates for the greater loss due to the greater radius of curvature of the stylus tip. According to (17b) λ_{co} is proportional to $(R/E)^{\frac{1}{3}}$, so that the cut-off wavelength λ_{co} for shellac ($R = 75 \mu$, $E = 6 \times 10^9 \text{ N/m}^2$) will be a factor of

$$\left(\frac{75}{25} \times \frac{3.3}{6}\right)^{\frac{1}{3}} = 1.18$$

greater than for co-polymer plastic ($R = 25 \mu$, $E = 3.3 \times 10^9 \text{ N/m}^2$). On the smallest diameter (9.5 cm) of a 78 r.p.m. record the groove velocity V_g is approx 1.85 times greater than on the smallest diameter (12.5 cm) of a 33 $\frac{1}{3}$ r.p.m. record, so that according to equation (1) the

cut-off frequency in the former case will be higher by a factor of $1.85/1.18 \approx 1.6$ than in the latter case.

- 6) The vertical force F_v , to which the stylus pressure is proportional, also affects ω_0 and λ_{co} as shown by (17): a reduction of the stylus pressure reduces λ_{co} and together with it the tracing loss, but ω_0 is then also reduced.

In a later article it will be shown how the above considerations have been applied in the design of a new pick-up.

Summary. As an introduction to an article on a new gramophone pick-up the mechanics of the system pick-up — gramophone record are considered. The stylus (sapphire, diamond) whose spherical tip rides in the groove of the record, causes elastic deformation of the groove walls. The convex wall is deformed to a greater depth than the concave wall. This causes a loss in the stylus deflection, the static tracing loss. This loss is greater the smaller the radius of curvature of the groove, i.e. the higher the frequency, the larger the amplitude and the nearer the stylus is to the centre of the disc. At a given frequency — the cut-off frequency — this loss is equal to the recorded signal, so that the stylus tip does not vibrate at all; this loss becomes apparent even considerably below the cut-off frequency.

A second effect — the dynamic tracing loss — has likewise the nature of a loss as long as the stiffness force of the pick-up exceeds the inertia force on the stylus tip; this is the case at frequencies below the free resonance frequency of the pick-up system. At higher frequencies this loss becomes negative and thus acts in opposition to the static loss. The total loss (the sum of the static and the dynamic losses) may even become negative. This is liable to happen particularly in the neighbourhood of the frequency at which resonance of the groove-wall stiffness and the effective mass at the stylus tip occurs; the resonance curve of this system is called the dynamic pick-up characteristic. A combination of the latter with the static characteristic produces the actual pick-up characteristic. According to whether the cut-off frequency lies higher or lower than the stylus-groove resonance frequency, the actual characteristic will either show a slight peak or no peak at all. The article is concluded with a discussion of the practical significance of the various properties of pick-up and record.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS BY THE STAFF OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk * can be obtained free of charge upon application to be Philips Research laboratory, Eindhoven, Netherlands.

- 2296:** P. W. L. Iterson and H. A. Teunissen: General outline of the development of transmitters for television and frequency modulation (T. Ned. Radiogenootschap **20**, 207-222, 1955, No. 3).

Description of some TV and FM transmitters together with their auxiliary equipment developed in recent years by Philips Telecommunications Industries. Some details are given of design and properties. Special features are the use of high power tetrodes, a special FM modulation circuit and unit

construction which lead to simple installations of high performance. An FM transmitter is described which works without supervision and switches over automatically to reserve equipment in the event of a failure.

- 2297:** H. O. Huisman, R. van der Veen and J. Meltzer: A new acaricide, 2,4,5,4'-tetrachlorodiphenylsulphone (Nature **176**, 515-516, 10 September 1955).

Note on the action of the above-mentioned acaricide. It acts on the eggs and larvae of a number

of mites but is ineffective against the fully-grown animals. The action is very selective: only mites are sensitive. Insects show no reaction and the acaricide is not poisonous to mammals.

2298: H. Groendijk and K. S. Knol: Characterization of the noise of tubes and transistors by four measurable quantities (T. Ned. Radio-genootschap **20**, 243-256, 1955, No. 4).

The noise of a neutralized triode is first calculated by investigating the mechanism of noise production and then by regarding the triode as a linear four-terminal network. It appears, from the first method, that the physical quantities connected with the generation of noise may not readily be determined. The second method shows, however, that it is still possible to characterize the noise by four measurable quantities and, once these are known, to calculate the noise factor. This holds for any linear four-terminal network, triodes, pentodes, transistors, etc. In general, no simple relationship exists between these quantities and the physical properties giving rise to noise. In the case of a triode the four quantities depend on frequency in a simple way. See also these abstracts No. R 277.

2299: J. A. Lely: Darstellung von Einkristallen von Siliciumcarbid und Beherrschung von Art und Menge der eingebauten Verunreinigungen (Ber. Deutsch. Keram. Gesellsch. **32**, 229-231, 1955, No. 8). (Preparation of single crystals of silicon carbide and control of type and quantity of lattice impurities; in German).

See these abstracts No. 2267.

2300: A. C. van Dorsten and J. H. Spaa: Een hoogspanningsgenerator in druktank voor neutronenproductie (Ned. T. Natuurk. **21**, 213-218, 1955, No. 9). (A pressurized high-voltage generator for neutron production; in Dutch).

Short description of equipment for producing a neutron flux of 10^{10} fast neutrons per second by the bombardment of a heavy ice target with deuterons. See Philips tech. Rev. **17**, 109-111, 1955/56.

2301: B. Combée, J. Houtman and A. Recourt: A sealed-off X-ray tube for contact-micro-radiography (Brit. J. Radiol. **28**, 537-542, October 1955).

Short description of a new sealed-off X-ray tube for contact microradiography using a 50 μ Be window (see also Philips tech. Rev. **17**, 45-46, 1955/56). Calculations and measurements are given concerning the properties of photographic emulsions

in the interesting range of wavelengths between 2-12 Å.

2302: M. Gevers: Measurement of dielectric and magnetic properties of solids at microwave frequencies (Proc. Symposium Precision Electrical Measurements, National Physical Laboratory, Teddington, Nov. 1954).

Description of two of the methods used for measuring dielectric and magnetic properties of solids at cm wavelengths in the Philips Research Laboratories, Eindhoven. At 10 cm a resonance method is used and at 3 cm a method based on standing waves. Special attention is paid to the sources of errors and the accuracy of the measurements on low loss materials.

2303: J. W. L. Köhler: Machines frigorifiques à gaz froid (Annexe 1955-2, Suppl. Bull. Inst. Int. Froid, pp. 13-23).

See Philips tech. Rev. **16**, 69-78 and 105-115, 1954/55. Special attention is paid in this article to the properties of the regenerator which include one condition not hitherto recognized.

2304: J. Volger: Pertes diélectriques de quelques verres et de substances similaires, mesurée aux basses températures (Annexe 1955-2, Suppl. Bull. Inst. Int. Froid, pp. 89-98).

The dielectric losses of quartz and various silicate glasses have been studied at low frequencies. Round about 50 °K a new type of loss — so-called deformation loss — appears. The relation between these phenomena and the glass structure is discussed.

2305: G. Diemer: Transit-time functions of a dynatron oscillator. (Appl. sci. Res. B **4**, 457-463, 1955).

The transit-time functions of the dynode admittance are discussed for a new type of dynatron-oscillator, in which the primary electrons are directed obliquely towards the dynode.

2306: J. A. Kok and M. M. G. Corbey: Breakdown of liquid insulating and dielectric material (Appl. sci. Res. B **4**, 474-475, No. 6).

Preliminary note on experiments and theory of long-term breakdown of liquid dielectrics at low frequencies.

2307: J. Meltzer: Het onderzoek van acariciden en spintoviciden in het laboratorium (Tijdschrift Plantenziekten **61**, 130-142, 1955). (The investigation of acaricides and red spider ovicides in the laboratory; in Dutch, summary in English).

Description of laboratory methods for the evaluation of acaricidal and ovicidal action of a large number of substances. The substances concerned fall into three groups: those active on adult mites, those active on eggs and immature mobile stages and those active on all three stages. The results are summarized in 13 tables.

2308: L. J. Tummers: Der Einfluss von Minoritäts-träger-Injektionen auf das Verhalten von Leistungstransistoren (Nachr.-techn. Fachber., 1955, No. 1, pp. 31-32). (The effect of minority carrier injection on the behaviour of power transistors; in German).

The emitter efficiency of a p-n-p alloy transistor with indium as the alloying material can be increased by adding a small amount of gallium or aluminium to the emitter indium. This improved emitter efficiency causes a more gradual fall off of the current amplification at increasing emitter currents and furthermore makes it possible to produce transistors with lower base resistance.

2309: J. C. van Vessem and Th. W. Willemse: Konstruktive Überlegungen beim Entwurf eines Leistungstransistors (Nachr. techn. Fachber. 33-36, 1955, No. 1). (Design considerations concerning power transistors; in German).

Design of a power transistor for a dissipation of 3 watts and description of the considerations which lead to this design.

2310: P. F. Moleman: Thermische Probleme bei der Verwendung von Schichttransistoren (Nachr. Techn. Fachber. 37-39, 1955, No. 1). (Thermal problems in the application of junction transistors; in German).

Study of the properties of a well-known circuit for the temperature stabilization of a transistor. When this circuit is used in a push-pull arrangement it is necessary to take account of the effect of temperature not only on the collector leakage current but also on the emitter-base potential difference.

2311: G. H. Jonker and H. R. Kruyt: Flocculation and recrystallization in freshly prepared silver bromide sols (Discussions Faraday Soc. No. 18, 170-190, 1954).

The ageing of diluted silver bromide sols has been studied by extinction measurements. The sols initially contain very small particles which flocculate to a certain degree, depending on the excess concentration of Ag^+ or Br^- ions. In very diluted sols

a new type of coarsening is found in the region of normally stable negative sols. By studying the influence of electrolytes, protecting colloids and temperature it is found that this new type of coarsening consists of two stages: first a recrystallization takes place to rather large crystals and then still larger particles are formed by oriented flocculation of the ideally formed crystals. The same effect has been found in sols of silver chloride at higher concentrations and in silver iodide at lower concentrations.

2312: F. A. Kröger and D. de Nobel: Preparation and properties of CdTe single crystals (J. Electronics 1, 190-202, 1955).

Single crystals of CdTe were prepared and purified using the method described in abstract 2313 (see below). By re-heating below the melting point under suitable atmospheres the stoichiometry and hence the electrical properties were modified. Both p and n type conductivity have been obtained. Measurements of Hall effect, the thermoelectric power and the resistance give values of the mobility and the effective mass of electrons and holes and an idea of the energies of donor and acceptor levels.

2313: J. van der Boomgaard, F. A. Kröger and H. J. Vink: Zone melting of decomposing solids (J. Electronics 1, 212-217, 1955).

Zone melting of substances which tend to decompose on heating can be accomplished by heating in an atmosphere of the component formed on decomposition. By means of the pressure of this component it is possible to control the composition of the crystals obtained from the melt. As an example, the growth of a PbS crystal with a p - n junction is described.

2314: R. Vermeulen: Stereophonie und Stereomachhall (Musik-Raumgestaltung-Elektroakustik, 1955, Ars vira Verlag, Mainz). (Stereophony and artificial reverberation; in German).

See Philips techn. Rev. 17, 258-266, 1955/1956.

2315: H. Koelmans and J. Th. G. Overbeek: Stability and electrophoretic deposition of suspensions in non-aqueous media (Disc. Faraday Soc. 1-12, 1954).

The stability of suspensions in solvents of very low polarity is treated in part 1 of this paper. Theoretical considerations lead to the conclusion, that quite modest electric charges and ζ -potentials are sufficient to stabilize suspensions of coarse particles ($> 1 \mu$) whereas hardly any stabilization

can be expected from adsorbed layers of non-ionized long-chain molecules. Experiments on the settling times of suspensions of a number of solids in xylene confirm that only ionized surface-active substances give rise to stability. Long-chain compounds that do not increase the conductance of the xylene, do not give rise to a sufficient ζ -potential of the particles and do not improve the stability very much. In part 2 electro-deposition from suspensions in polar organic media is investigated. It is shown that the particles are accumulated near the electrode by the applied field, but that the formation of an adhering deposit is caused by flocculation introduced by the electrolyte formed by the electrode reaction.

2316: A. G. Th. Becking, H. Groendijk and K. S. Knol: Kennzeichnung der Rauscheigenschaften von Vierpolen (Nachr. Techn. Fachber. 37-40, 1955). (Characterization of the noise properties of fourpoles; in German).

See abstract 2298 and abstract R 277.

2317: A. N. Diddens, F. L. H. M. Stumpers and J. Volger: Das Rauschen eines keramischen Halbleiters, dessen Widerstand von der Frequenz und von Magnetfeld abhängig ist (Nachr. Techn. Fachber. 88-89, 1955). (The noise of ceramic semiconductors whose resistance is dependent on frequency and on magnetic field; in German).

The noise voltage of a specimen of the material $\text{La}_{0.9}\text{Sr}_{0.1}\text{MnO}_3$, previously shown to have a frequency and magnetic-field dependent resistance, has been investigated. As expected the thermal noise satisfies the Nyquist formula $\overline{\Delta V^2}/\Delta f = 4kTR(f,H)$, where $R(f,H)$ is the real part of the impedance of the specimen at the frequency f and in the magnetic field H . A direct current i increases the noise strongly as in many polycrystalline materials. The spectrum of the current noise is given by $\overline{\Delta V^2}/\Delta f = K(f,H) i^\alpha f^{-\beta}$ where $\alpha = 1.3-1.7$, $\beta = 0.9$ and K is proportional to the value of $R(f,H)$.

2318: P. Schagen: The "scenioscope", a new television camera tube (T. Ned. Radiogenootschap 20, 291-305, 1955).

Description of a new television camera tube based on the use of a target of semi-conducting glass. See Philips tech. Rev. 17, 189-198, 1955/1956.

2319: J. Smit: The spontaneous Hall effect in ferromagnetics, I (Physica 21, 877-887, 1955).

Apart from the normal Hall voltage a magnetized ferromagnetic material usually shows a relatively large extra voltage in the same direction, which can

be found by linear extrapolation to $B = 0$. It is shown that this spontaneous Hall effect cannot exist in a perfectly periodic lattice. Measurements at different temperatures suggest that the effect is closely related with the electrical resistivity of the material. Existing theories on the origin of the effect are shown to be invalid, and it is shown that the explanation has to be based on the anisotropic scattering, caused by spin-orbit interaction of the conducting electrons against the imperfections of the lattice.

2320: R. Thoraeus, W. J. Oosterkamp, J. Proper, R. Jaeger, B. Rajewsky, E. Bunde, M. Dornreich, D. Lang and A. Sewkor: Vergleichsmessungen der internationalen "röntgen" im Bereich von 8 kV bis 170 kV Erzeugungsspannung (Strahlentherapie, 18 (2), 1955). (Comparative measurements of the international röntgen for generating voltages from 8 kV to 170 kV; in German).

Joint publication from the Radiofysika Institutionen. Stockholm, the Philips Research Laboratories, Eindhoven, the Physikalisch-technische Bundesanstalt, Braunschweig and the Max Planck-Institut für Biophysik, Frankfurt/Main. The main results are given of a comparison between the standard instruments for measuring hard and soft X-rays of the Max Planck Institut für Biophysik and Swedish and Dutch instruments. The measurements with hard X-rays are in good agreement with each other. The comparisons in the soft X-ray region, where errors are by nature larger, show fairly good agreement; studies are planned to improve measuring instruments and methods in this region in order to reduce the still existing differences.

2321: J. W. L. Köhler and J. van der Ster: A small liquid nitrogen plant using a gas refrigerating machine (Proc. 9th Int. Congress Refrigeration, Paris, Sept. 1955).

Description of an installation producing liquid nitrogen on a small scale. A rectifying column is coupled to a gas refrigerating machine supplying the necessary cold. The air to be fractionated is not compressed at all, which makes the installation extremely simple. The single column is of the packed type; the incoming air is utilized to reboil the liquid with the higher boiling point. The vapor, issuing at the top of the column, is condensed by the gas refrigerating machine: the resulting liquid is partly utilised as reflux in the column, the rest forming the product. The completely automatic plant is run fully unattended. Relevant constructional details and results are given.