A LOUDSPEAKER INSTALLATION FOR HIGH-FIDELITY REPRODUCTION IN THE HOME

by G. J. BLEEKSMA and J. J. SCHURINK.

For more than a quarter of a century the normal broadcast receiver has been equipped with a single loudspeaker fitted inside the cabinet. The introduction of sets with two separate speakers, each reproducing part of the frequency spectrum on the Philips "Bi-Ampil" principle, dates only from the last few years.

The installation described in this article goes a big step further, the loudspeakers being entirely separated from the amplifying part; two low-note speakers are together housed in a special cabinet and two high-note speakers separately in their own boxes. The quality of reproduction has been remarkably improved in this way, which appears to full advantage with F.M. reception and the play-back of gramophone records or tape recordings.

A complete system for sound reproduction, from performance to play-back can be considered as a chain whose first link is formed by one or more microphones and whose final link is made up of one or more loudspeakers. In between are one or more amplifiers, and further either a radio link or some "memory" with play-back facilities. (The "memory" is normally a tape recording or a gramophone record.)

The links in this chain are not equally strong. "Strong" links are those that are unlikely to be hardly improved upon by present engineering practice. As such we may consider the condenser microphone and the amplifiers. The memory is among the weaker links. However high the quality of magnetic recordings and modern gramophone records may be, certain improvements in the step function response and in the dynamic characteristic are still desirable.

Loudspeakers too should be considered as among the weaker links. A recent development in this field forms the subject of this article. The installation described is in our opinion about the very best attainable for home entertainment that can be realized with the technical means now at our disposal.

Brief description of the installation

The installation comprises four loudspeakers, viz. two for the low notes (with a range below 420 c/s) and two for the frequency range above 420 c/s (referred to here briefly as the high range). The two low-note speakers are together housed in a corner cabinet (fig. 1), whilst the high-note speakers are contained in separate boxes (fig. 2). All these loudspeakers are fed by one amplifier (type AG 9000 or AG 9006), via a low-pass and a high-pass filter respectively.

The loudspeakers for the frequency range above 420 c/s radiate nearly all their energy in a forward direction, and for this reason they are called projectors. Separate projectors can be so placed that their sound reaches the listeners only indirectly, i.e. via one or more reflections from the walls or the ceiling of the room. The importance of this method is that it diffuses the sound, so that the result approaches far more closely the actual conditions in the concert hall. Measurements in various concert halls have revealed that at most places in the hall the greater part of the sound intensity is attributable to indirect sound and only a small part to direct radiation. Similar conditions can be created in the living-room by directing the projectors at different walls of the room in such a way that the listeners are outside the direct beams (fig. 3). The position of the low-note cabinet is less critical, since the directions from which the low notes issue are more difficult to distinguish.

The use of two projectors, placed some distance apart from each other and from the listeners, effectively avoids the "hole-in-the-wall" effect. This can be explained as follows. Let us assume that we are listening to an orchestre via one loudspeaker only. Even if the whole reproduction channel reproduced uniformly the entire frequency spectrum and were completely devoid of distortion and...
dynamic limitations, the reproduction would still remain unsatisfactory in one respect: the entire orchestra, set up on a wide podium, would be heard as if it were compressed into the small aperture of the loudspeaker, i.e. as if the orchestra was listened to through a hole in the wall of the concert hall.

An effective means of remedying this hole-in-the-wall effect is stereophony 6), but this is only seldom used in radio broadcasts or with gramophone records. However, by placing the two projectors in such a way that the sound reaches the listeners only indirectly, the hole-in-the-wall effect can be eliminated.

The high-note speakers (type 9710 M) are distinguished from the low-note speakers (type 9710) in that they are double-cone loudspeakers 7). As can be seen in fig. 4, the moving coil drives not only a normal cone \((C_1)\) but also a small auxiliary cone \((C_2)\). The latter extends the frequency range, which would normally reach no further than 8 kc/s, to about 18 kc/s, and at the same time blurs the sharp outlines of the beam.

The reproduction of the high notes is further improved by the use of loudspeakers with nearly constant impedance: at 20 kc/s the impedance of a type 9710 M loudspeaker is only 1.5 times as high as at 400 c/s, whereas for conventional loudspeakers this ratio is at least 5. When fed with a constant voltage, the current flowing through such "constant-

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6) See e.g. the article quoted in 4), p. 173 et seq.
impedance" loudspeakers will therefore decrease considerably less with rising frequency than the current flowing through conventional loudspeakers. The reproduction of the high-note range will consequently be superior, since it is the current that determines the force with which the cone is driven.

Fig. 3. A typical arrangement of the units. To the right is the cabinet containing the gramophone and the amplifier, and in the corner the low-note cabinet. The two high-note projectors are so arranged that a diffused sound is obtained.

Fig. 4. The double-cone loudspeaker 9710 M of the high-note projector. In the cross-section, $C_1$ is the main cone, $C_2$ the auxiliary inner cone, $S$ the coil, $D$ the centring ring, $R$ the corrugated cone edge, $M$ the permanent magnet, and $K$ the copper ring ensuring a constant impedance (see further in this article). The core $P$ of the magnetic circuit has a conical hole for accommodating the top of cone $C_1$. 
The cabinets in which the loudspeakers are housed are completely closed behind the cone. As regards the high-note projectors this prevents any back radiation (possibly directed at the listeners) which would mar the diffusion effect aimed at. As regards the low-note loudspeakers the closed box prevents the air vibrations from travelling round the cone; it thus represents an infinitely large baffle, which greatly enhances the reproduction of the very low notes. The enclosed volume of air, as we shall demonstrate later in this article, also helps in reducing non-linear distortion. To attain the best possible enclosure, “complete cones” have been used instead of the conventional truncated cone (fig. 4).

After this brief description, we shall now consider some of the above-mentioned features more closely, starting with the forms of distortion caused by non-linear phenomena.

Non-linear distortion in loudspeakers

The speech coil of a moving-coil loudspeaker, through which a current \( I \) flows, is situated in a magnetic field with an induction \( B \). A force \( F = BI \) then operates on the coil (\( I \) denoting the length of wire in the speech coil). Since a force is numerically equal to the reaction it produces, this force is equal to the product of the mechanical impedance \( Z_m \) and the velocity \( v \):

\[
BI = Z_m v = \left( j \omega M + \frac{1}{j \omega C} + R_m \right) v. \tag{1}
\]

In this expression \( \omega \) is the angular frequency of the current, \( M \) the mass of the coil and cone and that of the air that moves with the cone, \( C \) the total compliance (i.e. the reciprocal of the stiffness) and \( R_m \) the mechanical resistance (both the resistance of the effective sound radiation and the mechanical loss resistance, the latter mainly occurring in the edge of the cone and in the centring ring).

The displacement \( x \) of the coil at the moment \( t \) is given by \( x = \int v \, dt \), and hence

\[
x = \frac{v}{j \omega} = \frac{BI}{C - \omega^2 M + j \omega R_m}. \tag{2}
\]

The resonance frequency \( f_0 \) of the system is therefore:

\[
f_0 = \frac{1}{2 \pi \sqrt{MC}}. \tag{3}
\]

Because of the resistance term in (2), the displacement will be greatest at a frequency below \( f_0 \).

It also appears from (2) that at frequencies that are sufficiently above the resonance frequency the displacement varies about proportionally with \( \omega^2 \), and hence by 12 dB per octave (the current remaining constant). In this frequency range the amplitude is so small that no distortion is noticeable. At frequencies sufficiently below the resonant frequency, however, the displacement is given by

\[
x \approx CBII. \tag{4}
\]

Here the amplitude can become so large that the relation between \( x \) and \( I \) is no longer a linear one as the result of two causes: 1) the induction \( B \) in the air-gap is not quite homogeneous, so that \( B \) depends upon \( x \) (at very large amplitudes the coil comes even partly out of the air-gap), and 2) the compliance \( C \) is dependent on \( x \) to an even higher degree. With a sinusoidal current this non-linear distortion will produce harmonics, so that the timbre of the sound will be different. Moreover, if the current consists of two (or more) sinusoidal components, non-harmonic overtones are likely to occur, which are displeasing to the ear. We shall now separately consider these two forms of distortion.

Harmonic distortion

It can be seen from fig. 5a that the factors \( B \) and \( C \) in (4) are not constants. The dot-dash lines of this diagram represent the force \( F \) (plotted horizontally) operating on the coil in the magnetic field, at different values of a direct current \( I \) passing through the coil. The force \( F \) is strictly proportional to \( I \), but varies with \( x \), since \( B \) varies with the position in the air-gap. If the field were homogeneous, all these lines would be straight and vertical. If the displacement \( x \) of the currentless coil is measured statically as a function of an external force \( F \), we arrive at a hysteresis loop as represented by the fully drawn curve in fig. 5a. This shows that the total compliance \( C_c \) of the cone edge and the centring ring (the only compliances operative here) depends upon \( x \) and thus likewise has a non-linear character.

The variation of \( x \) as a function of time, for a sinusoidal current, can be derived from the curves in fig. 5a. As expected, the original sinusoidal waveform is considerably distorted and a number of higher harmonics occur in the displacement. As regards the sound pressure \( p \), this effect will be even more pronounced since the pressure variations are proportional to \( \omega^2 x \), so that the subsequent harmonics in \( p \) are respectively 1, 4, 9, ... times greater than those in \( x \). For instance, 1% of third harmonic in \( x \) results in 9% of third harmonic in \( p \).
Non-harmonic distortion can be attributed to still another cause, viz. the Doppler effect. If a loudspeaker cone vibrates simultaneously with a low frequency $f_1$ and a higher frequency $f_2$, then it may be considered as a source of sound with frequency $f_2$ whose distance to the ear varies with the frequency $f_1$. Owing to the Doppler effect the pitch will then fluctuate with the rhythm of the low frequency $f_1$ around the higher frequency $f_2$, so that frequency modulation occurs. This can be interpreted as the presence of a sound with central frequency $f_2$ and two side-bands in which the frequencies $f_2 \pm m f_1$ occur. Let the amplitudes of the vibrations with the frequencies $f_1$ and $f_2$ be $x_1$ and $x_2$ respectively, then the amplitudes of the first and the second side-band components will amount to
\[
10^{-2} x_1 f_2 \% \quad \text{and} \quad 5 \times 10^{-7} \times (x_1 f_2)^2 \% \quad \text{of} \quad x_2,
\]
$x_1$ being expressed in cm and $f_2$ in c/s. For example, if $x_1 = 0.1$ cm and $f_2 = 10000$ c/s we find: 10% for the components with the frequencies $f_2 + f_1$ and $f_2 - f_1$, and 0.5% for the components with the frequencies $f_2 + 2f_1$ and $f_2 - 2f_1$.

Means of reducing distortion

Doubling the number of loudspeakers

For reducing the non-linear distortion there exists a solution so simple that its value is not always fully appreciated. We refer to the use of more than one loudspeaker (quite apart from the separation of low and high notes). To attain an equivalent total sound volume each individual cone can then vibrate with a smaller amplitude, so that a shorter and less curved part of the hysteresis loop (fig. 5a) is used, and the coil operates within a more uniform magnetic field.

For this reason we are using two low-note loudspeakers in our installation (the two high-note speakers are used mainly to diffuse the sound, distortion at higher frequencies being anyway very slight).

As for the low-note reproduction, this particular aim — less distortion through smaller amplitude, at equal total sound volume — might also be attained in principle by using instead of two adjacent loudspeakers with radius $a$ (fig. 6a), a single loudspeaker with radius $a/\sqrt{2}$ (fig. 6b).

Let us first compare one "small" loudspeaker (radius $a$, fig. 6a) with one "large" loudspeaker (radius $a/\sqrt{2}$, fig. 6b). Their radiation resistances are proportional to the fourth power of their radii. The large speaker, therefore, has a radiation resistance ($1/2^4 = 4$ times greater than that of the small loudspeaker. At the same amplitude $x$ the large loudspeaker will radiate four times more power.
When the large loudspeaker is to be compared with a combination of two small ones then one would expect, if each small speaker, operating separately, radiates a power $P$, that they would produce together a power $2P$, and that therefore the large loudspeaker, with $4P$, would be twice as powerful. It should be taken into account, however, that the effect of two small loudspeakers close together is different from that of the same two speakers some distance apart. Two loudspeakers (vibrating in phase) in close proximity produce the favourable effect that they stimulate each other, as it were, to radiate a greater power.

This effect can be readily explained as follows: if the loudspeakers are far apart (fig. 6d), then each yields energy to the air, since the cone is moving against self-produced pressure variations. If, however, the loudspeakers are close together (fig. 6c), then in addition to the self-produced pressure variations there will be those from the adjacent loudspeaker. Owing to the small distance, these pressure variations are virtually equal in amplitude and phase. Each of the cones, then, operates against a sound pressure that is twice as high and thus produces double the amount of power. The two loudspeakers together now produce a power that is twice as large as when they are placed far apart (for a constant amplitude $\tilde{x}$ of the cone displacement).

Klapman has evaluated this effect for intermediate cases, viz. for two loudspeakers, considered as flat pistons (radius $a$, distance between centres $d$) $^8$). Fig. 7a shows the curve plotted for $R_r/(\rho c A)$ ($R_r =$ radiation resistance per piston, $\rho =$ air density, $c =$ velocity of sound, $A =$ area of each piston) as a function of $2\pi fa/c$, with $d$ as parameter. For the type 9710 loudspeaker $2a = 17.5$ cm; the frequency scales added to fig. 7 apply to this value. In the cabinet the loudspeakers are placed at a distance $d = 2.8 a$. In the frequency range in question (below 420 c/s) $R_r$ is substantially greater than would be the case with a single loudspeaker (curve for $d = 0$).

In the above imaginary experiment, in which two loudspeakers are brought closer together, the amplitude $\tilde{x}$ was assumed to remain constant. If, however, the supply current is kept constant when the loudspeakers are approaching each other, $\tilde{x}$ will decrease a little (thus reducing the advantage), because an increasing amount of air will move with the cones. This moving mass of air gives rise to a reactive component ($X_r$) of the mechanical impedance. The curve of this component has likewise been evaluated by Klapman (fig. 7b).

A large cone, however, has the drawback that it must be relatively heavy to be sufficiently rigid. The loudspeakers used here (type 9710), with \(2a = 17.5\) cm, are preferable in this respect to a loudspeaker with \(2a = 17.5 \sqrt{2} = 25\) cm, the cone of which is more than twice as heavy.

**Loudspeakers in closed cabinets**

A second means of reducing distortion is to enclose a given volume of air behind the cone. The enclosed air represents a stiffness \(S_a\) which, unlike the rigidity \(S_c\) of cone edge and centring ring, remains satisfactorily constant and thus tends to improve the linearity of the entire system.

In order to find to what extent \(S_a\) still deviates from true linearity, we shall consider an enclosed quantity of air under a piston. If the latter is given a displacement \(\Delta x\), then the air rigidity, \(S_a\) exerted on the piston can be written as:

\[
S_a \approx \frac{\rho_0 c^2 A^2}{V_0} \left[ 1 + \frac{1}{2} (\kappa + 1) \frac{A}{V_0} \Delta x \right] \quad (7)
\]

(the process being assumed as adiabatic). Here \(\rho_0\) represents the density and \(V_0\) the volume of the air in the state of equilibrium, \(A\) the area of the piston and \(\kappa\) the ratio \(c_p/c_v\) of the specific heat of air at constant pressure to that of air at constant volume (\(\kappa \approx 1.4\)).

Formula (7) can be derived as follows. An adiabatic process occurs according to

\[
p V^\kappa = \text{constant}
\]

\((p = \text{air pressure}, \ V = \text{air volume})\). For a displacement of the piston causing the pressure to increase from \(p_0\) to \(p_0 + \Delta p\) and the volume to decrease from \(V_0\) to \(V_0 - \Delta V\), we arrive at

\[
(p_0 + \Delta p) (V_0 - \Delta V) = p_0 V_0^\kappa.
\]

From this we obtain

\[
\frac{\Delta p}{\Delta V} = \frac{\kappa p_0 [V_0^{-1} + \frac{\kappa + 1}{2} V_0^{-2} \Delta V + \frac{(\kappa + 1)(\kappa + 2)}{3!} V_0^{-3} (\Delta V)^2 + \ldots]}{p_0 V_0^{\kappa - 1}}.
\]

The stiffness \(S_a\) can be defined as \(\Delta F/\Delta x\), \(\Delta F\) being the force necessary to bring about a displacement \(\Delta x\) of the piston. Here \(\Delta F = A \Delta p\) and \(\Delta x = \Delta V/\Delta x\), so that:

\[
S_a = \frac{\Delta F}{\Delta x} = A^2 \frac{\Delta p}{\Delta V} = \frac{x_p A^2}{V_0} \left[ 1 + \frac{\kappa + 1}{2} \frac{A}{V_0} \Delta x + \frac{(\kappa + 1)(\kappa + 2)}{6} \frac{A^2}{V_0^2} (\Delta x)^2 + \ldots \right]. \quad (8)
\]

With the help of the relation \(c = \sqrt{\frac{x_p A^2}{\rho_0}}\), the product \(x_p A^2\) in the right-hand term of (8) can be written as \(\rho_0 c^2\). By substituting this value and disregarding the terms containing \((\Delta x)^2\), \((\Delta x)^3\), etc. in (8), we arrive at equation (7).
The term $\frac{1}{2}(x+1)A\Delta x/V_0$ represents the non-linearity of $S_a$. In fig. 8 this term is expressed as a percentage and plotted as a function of the enclosed air volume $V_0$, with the diameter $2a$ of the cone as parameter; this diagram applies to the extremely large amplitude $x (= \Delta x) = 10$ mm. It then appears that the non-linearity in $S_a$ can be kept below 0.5% by a proper selection of $2a$ and $V_0$ (e.g. $2a = 17.5$ cm, such as that of the loudspeaker 9710, and $V_0 = 70$ l, which is half the volume of the low-note cabinet; this gives 70 l per loudspeaker).

Fig. 10. Equivalent diagram of a loudspeaker with a cone compliance $C_c$, for a compliance $C_o$ of the enclosed air volume behind the cone. The self-inductance $M_c$ represents the effective mass of the cone and of the air moving with it; the resistance $R_m$ the sum of the radiation resistance and the loss resistance.

Owing to this enclosure of a quantity of air behind the cone, the total stiffness $S$ becomes $S_a + S_o$; the non-linearity of the cone stiffness $S_a$ appears from the hysteresis loop in fig. 5a. It is evident that because $S_a$ is virtually linear, $S$ will show relatively less distortion than $S_o$, and the less so as $S_a$ is greater and therefore as the air volume $V_0$ is smaller (see eq. (7) and also fig. 9, which represents the linear part of $S_a$ as a function of $V_0$ with $2a$ as parameter).

The air rigidity cannot be indiscriminately enlarged since it is associated with an increase in the resonance frequency of the cone. This is revealed by (3),—which now assumes the following form:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{M}{C_c C_o}} = \frac{1}{2\pi} \sqrt{\frac{M}{S_c + S_o}}$$

($C_c = 1/S_c$ and $C_o = 1/S_o$ are the compliance values; cf. the equivalent diagram fig. 10). The resonance frequency lies only slightly below $f_o$, and the former must be confined to the lowest regions of the frequency range to be reproduced. The resonance frequency of the type 9710 loudspeakers without cabinet is about 40 c/s. The cabinet for the low-note speakers (fig. 1) is made so large (70 l per loudspeaker) that $S_a$ considerably exceeds $S_c$ ($S_a = 1200$ N/m, $S_c = 750$ N/m). This has raised the resonance frequency to about 60 c/s. By using electric damping (cf. the section The Amplifier at the end of this article) this resonance peak has been sufficiently flattened out.

The high-note speakers are likewise accommodated in closed boxes, but here the object is to prevent back radiation. The boxes can be small (fig. 2) — and therefore the air rigidity great — since the resonance frequency of these speakers can quite permissibly be raised to about 300 c/s. In fact, a high resonance frequency is an advantage since it helps to suppress low notes, and so reinforces the effect of the electric filter, to be discussed presently.

Division of the frequency range

In the foregoing, intermodulation and Doppler effect were mentioned as causes of non-harmonic distortion. Both can be effectively combated by splitting up the audio range and reproducing it by separate loudspeakers.

It was found that in practice a division into two parts, as applied in the installation discussed here, is sufficient. As to the question at what frequency this division can best be made, it was decided to make the cross-over frequency 420 c/s. Combination tones of the type $\pm m f_1 \pm n f_2$, where $f_1$ is low (e.g. 50 c/s), are especially objectionable if $f_2$ is higher than about 400 c/s, so that the cross-over frequency should preferably not be fixed much higher than this value.

The filter effecting the separation of the high and low notes consists of two coils with self-inductance $L$ and two capacitors of capacitance $C$, connected as shown in fig. 11. The impedance of each of the speakers is a nearly frequency-independent resistance $R_1$, amounting to 7 $\Omega$ for the low-impedance speakers, and to 400 or 800 $\Omega$ for the high-impedance ones. (How this constant impedance has been achieved will be discussed later in this article.) Let the internal resistance of the amplifier be negligible, and $E$ be its output voltage; we then find for the
current $I_1$ through the low-note speakers and $I_h$ through the high-note projectors:

$$I_1 = \frac{E}{2 \left(1 - \omega^2 LC\right) R_1 + j\omega L}$$

and

$$I_h = \frac{E}{2 \left(1 - \frac{1}{\omega^2 LC}\right) R_1 - j\omega C}$$

The formulae may be written as:

$$I_1 = \frac{E/2R_1}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(\frac{\omega}{\omega_0}\right)^2}} \quad (9)$$

and

$$I_h = \frac{E/2R_1}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(\frac{\omega}{\omega_0}\right)^2}} \quad (10)$$

where

$$\omega_0^2 = \frac{1}{LC}$$

and

$$\delta = \frac{1}{2R_1} \sqrt{\frac{L}{C}} \quad (11)$$

$\delta$ being the damping factor.

In order to give each network the desired pass band (fig. 12), $L$ and $C$ must be so chosen that

$$\frac{1}{2\pi \sqrt{LC}} = 420 \text{ c/s} \quad (12)$$

and there must also be adequate damping $\delta$. For critical damping (aperiodic system without free vibrations), $\delta$ must be at least 2. In that case, however, the currents $I_1$ and $I_h$ are insufficiently constant in their pass bands; at the cross-over frequency they will drop by as much as 6 dB below the value $E/2R_1$ which they respectively assume at very low and very high frequencies (see the dotted curves in fig. 12). For obtaining a flatter characteristic we have preferred a somewhat smaller damping, viz. $\delta = \sqrt{2}$. The fully drawn curves in fig. 12, which drop only 3 dB below $E/2R_1$ at the cross-over frequency, represent this damping value. Outside the pass bands the drop in the curves approaches 12 dB per octave, i.e. $I_1$ decreases at high frequencies proportionally to $f^{-2}$ and $I_h$ increases at low frequencies proportionally to $f^2$, which is also apparent from the formulae (9) and (10).

If $R_1$ is known, $L$ and $C$ are completely determined by (11), (12) and the value selected for $\delta$. For example, when $R_1 = 7 \Omega$ we find: $L = 7.4 \text{ mH}$ and $C = 20 \mu\text{F}$, which are the values used for low-impedance loudspeakers.

Some further details regarding the cabinets

One advantage of operating the loudspeakers in completely enclosed cabinets is, as we demonstrated earlier, a reduction of distortion, as a result of the additional air rigidity. Another advantage, at least as regards the low notes, is the fact that the sound waves cannot travel around the cone (the same as if the baffle were infinitely large). This latter point may be elucidated as follows.

The sound radiation of a vibrating diaphragm is impaired if the air vibrations are allowed to travel along a short path around the diaphragm. This is why this path is usually lengthened by placing the diaphragm in a baffle 9), e.g. inside a cabinet. Let $l_0$ be the shortest path from the front to the rear of the diaphragm around the baffle, then we may apply the rule of thumb that the sound emission decreases by 6 dB per octave if the frequency drops below the value relating to a wavelength $\lambda = 2l_0$. For a frequency of 50 c/s, for instance, the wavelength is more than 6 m. An enormous baffle would thus be required for a satisfactory reproduction of very low notes.

In the installation described here this has been circumvented by fitting the bass-note speakers in a completely enclosed cabinet which, just as an infinite baffle, prevents even the longest waves from traveling around.

With any cabinet, however, whether closed or not, there is a risk that it will act as a resonant cavity and give rise to standing waves due to reflection against...
the walls of the cabinet. This has been avoided by covering the interior of both the high and the low-note cabinets with a sound-absorbent material.

No special problems were involved in this procedure for the high-note cabinet, since there are several materials commercially available that adequately absorb the higher audio frequencies. For the lower frequencies, however, the solution was not so simple. In this case the principle of “panel resonance” was adopted. The inside of the cabinet was fitted with panels mounted on a framework of laths, leaving an air cushion between these panels and the walls of the cabinet (fig. 13). Owing to the resonator interaction of the mass of the panel with the stiffness of the air cushion, an adequate absorption through the low-note range is achieved, mainly as a result of the dissipation in the clamped-in edges of the vibrating panels. The panels, consisting of an absorbent material, furthermore bring about ordinary absorption in the upper part of the low-note range.

There must be sufficient absorption over a certain frequency range. This range is determined by the following. The most important of the natural vibrations of the cabinet are those for which \( \lambda/4 \) or \( \lambda/2 \) is equal to one of the interior dimensions of the cabinet. The largest interior dimension is 70 cm, so that the lowest frequency of the natural vibrations is \( \frac{c}{4 \times 0.70} = 120 \text{ c/s} \). By giving the panels a natural frequency \( f_p = 240 \text{ c/s} \) and making this resonance not very selective, adequate absorption is obtained in the entire range from 120 to 420 c/s (in the upper part of this range, assisted by the absorption of the material itself). In connection with dimensioning the resonator such that \( f_p = 240 \text{ c/s} \), the following should be pointed out. By analogy with eq. (3), we may write:

\[
f_p = \frac{1}{2 \pi} \sqrt{\frac{S}{M}}.
\]

\( f_p \) represents mainly the frequency \( f_p \) of the air cushion behind the panel, \( M \) mainly the mass \( M_p \) of the panel; the stiffness of the panel at the edges and the mass of the air moving with the panel may be neglected to a first approximation. According to (7), \( S_a \) can be written as

\[
S_a = \frac{\varrho_0 c^2 A_p^2}{A_p d_a},
\]

\( \varrho_0 \) being the density of the air, \( A_p \) the area of the panel and \( d_a \) the thickness of the air cushion (panel-wall distance). \( M_p \) can be written as

\[
M_p = A_p d_p \varrho_p,
\]

\( d_p \) being the thickness of the panel and \( \varrho_p \) the density of the absorbent material. By substituting (14) and (15) in (13) we arrive at:

\[
f_p = \frac{c}{2 \pi} \sqrt{\varrho_0 \varrho_p d_p d_a}.
\]

Now \( c = 340 \text{ m/s} \) and \( \varrho_0 = 1.3 \text{ kg/m}^3 \). The density \( \varrho_p \) of the absorbent material used is 55 kg/m\(^3\). For \( d_p = 50 \text{ mm} \) and \( d_a = 25 \text{ mm} \) (fig. 13) we find \( f_p \) = approx. 240 c/s.

Loudspeakers with constant impedance

The self-induction of the speech coil causes its impedance to increase with the frequency (see the dotted curve in fig. 14). If the coil is fed with a frequency-independent voltage, the current, and consequently the force driving the cone, will decrease with increasing frequency. As mentioned in the description of the installation, the loudspeakers used have a virtually constant impedance. This is owing to the introduction of a copper ring (K, fig. 4) within the coil. This ring operates as a short-circuited winding and thus mainly eliminates the self-induction of the coil\(^{10}\). The result is the

\[
\text{Fig. 14. Impedance } Z_i \text{ of a loudspeaker divided by the D.C. resistance } R_i, \text{ as a function of the frequency } f. \text{ Ordinary loudspeaker: dotted curve; loudspeaker with short-circuiting ring: full curve.}
\]

\({10}\) A ring of this type was mentioned in the Philips tech. Rev. 4, 301, 1939, footnote 1).
impedance curve shown as the fully drawn line in fig. 14. Between the frequencies 400 c/s and 18 kc/s the impedance changes only in the ratio 1:1.5; without short-circuiting ring this ratio would be between 1:5 and 1:6.

The optimum shape and dimensions of the short-circuiting ring can be determined from the following analysis.

Let $E_1$ be the terminal voltage and $I_1$ the current through the coil (of resistance $R_1$ and self-inductance $L_1$), and $I_2$ the current induced in the short-circuiting ring (of resistance $R_2$ and self-inductance $L_2$); the impedance $Z_i = E_i/I_i$ of the coil is then given by:

$$Z_i = R_1 + \frac{k^2L_1R_2}{1 + \left(\frac{R_2}{\omega L_2}\right)^2} + j\omega L_1\left[1 - \frac{k^2}{1 + \left(\frac{R_2}{\omega L_2}\right)^2}\right] + Z'. \quad (16)$$

In this equation $k$ represents the coupling factor $= \sqrt{M_2/L_1L_2}$ ($M_2$ being the mutual induction between coil and ring), and $Z'$ represents a term accounting for the e.m.f. induced in the moving coil. The motion of the coil, however, does not alter the alternating flux linked by the ring. In order to determine the influence of the ring on the impedance of the coil it is therefore permissible to consider the coil as being stationary, i.e. to put $Z' = 0$; to distinguish $Z_i$ in this case we shall call it $Z_{10}$. As regards "low" frequencies ($\omega \ll R_1/L_2$), equation (16) can be written as

$$Z_{10} \approx R_1 + j\omega L_1, \quad \ldots \quad (16a)$$

and as regards "high" frequencies ($\omega \gg R_1/L_2$) as

$$Z_{10} \approx (R_1 + k^2L_1R_2/L_2) + j(1 - k^2)\omega L_1. \quad (16b)$$

The dimensions of the ring should be such that the following conditions are satisfied:

1) The frequency at which $\omega L_2 = R_2$ must be so low that $\omega L_2$ is still small with respect to $R_1$ (e.g. below 2 kc/s), so that at "low" frequencies (see eq. (16a)) $Z_{10} \approx R_1$.

2) The coupling between ring and coil must be very tight, so that the factor $(1 - k^2)$ in (16b) is sufficiently small to keep the term $(1 - k^2)\omega L_2$ small with respect to the resistance term up to the highest audio frequencies.

Both requirements can be satisfactorily met. It should be noted that compliance with 1) means that also the quantity $k^2L_1R_2/L_2$ by which the resistance term in (16b) differs from $R_1$ is small with respect to $R_1$. With an appropriately dimensioned ring, therefore, the efficiency of the loudspeaker is not appreciably reduced.

The question arises whether, with a loudspeaker without copper ring, the two soft-iron boundaries of the air-gap would not act as short-circuiting rings. This effect, however, is negligible, owing to the skin effect, which is far more pronounced in iron, with its fairly high permeability and rather poor conductivity, than in copper. With the copper ring no skin effect is noticeable since the penetration depth of the current is greater than the thickness of the ring, even at 20 kc/s. This means that the current is virtually uniformly distributed over the cross-section of the ring, so that $R_2$ is practically equal to the D.C. resistance of the ring.

The amplifier

As mentioned above, the bass-note loudspeakers in their cabinet show a mild resonance peak around 60 c/s. To provide a further damping of this resonance, the amplifier should have a low internal resistance.

The influence of the internal resistance upon the damping can be explained as follows. Owing to the motion of the coil (wire length $l$, velocity $v$) an e.m.f. $Blv$ is induced in it. This e.m.f. operates on the resistance $R_1$ of the coil in series with the internal resistance $R_i$ of the amplifier ($R_i$ measured at the output terminals). These two resistances thus have to dissipate a power $(Blv)^2/(R_1 + R_i)$. Instead of this, let us imagine an equal dissipation in an imaginary mechanical resistance $R_{m'}$:

$$\frac{(Blv)^2}{R_1 + R_i} = R_{m'}v^2,$$

and hence

$$R_{m'} = \frac{Blv^2}{R_1 + R_i}.$$

The mechanical damping resistance already present is consequently raised by this amount, $R_{m'}$ being larger the lower the internal resistance $R_i$ of the amplifier.

An effective means of reducing the internal resistance is the use of voltage feed-back, i.e. part of the output voltage is applied in anti-phase to the input voltage of the output stage or of a previous stage.\(^\text{11}\)

The splitting-up into two frequency ranges after the amplifier requires an amplifier that is adequately designed to prevent any appreciable intermodulation. The amplifiers AG 9000 and AG 9006 (fig. 1) are very suitable in this respect, respectively supplying 10 and 20 W output at 2% intermodulation. The former amplifier has been designed for loudspeakers with the conventional low resistance (two 7 Ω speakers in series) and is therefore equipped with a step-down output transformer. The amplifier AG 9006, on the other hand, contains a novel output circuit, capable of directly feeding high-impedance loudspeakers\(^\text{12}\); the output transformer with its inevitable distortion is thus obviated here.


\(^\text{12}\) An article on output circuits for high-impedance loudspeakers will appear shortly in this Review.

Summary. The high-fidelity loudspeaker installation for the home described here comprises a corner cabinet with two bass-note loudspeakers, two separate boxes for the higher frequencies, each containing a double-cone loudspeaker, and filters for splitting up the audio spectrum into two ranges, one below and one above 420 c/s. By appropriately positioning the high-note loudspeakers, good diffusion of the sound can be achieved. The listener then hears mainly indirect sound, just as in the concert hall. The so-called hole-in-the-wall effect, which is a drawback of reproduction by a single loudspeaker, is thus eliminated.
One cause of non-linearity in moving-coil loudspeakers is the amplitude-dependence of the stiffness of the cone suspension. The influence of this has been greatly reduced, 1) by doubling the number of loudspeakers, so that the cones can vibrate with a smaller amplitude, and 2) by adding a considerable, practically linear air stiffness. The latter was achieved by using completely closed cabinets. For low-note reproduction this has the additional advantage that the air waves cannot travel around the cone, whilst the high-note speakers will not emit any sound to the rear. Standing waves inside the cabinet are prevented by lining the cabinets with an absorbent material (in the low-note cabinet in the form of panels separated from the walls by an air cushion). Non-harmonic distortions (intermodulation and Doppler effect) have been greatly reduced by dividing the total frequency range into two parts. The overall reproduction extends from about 20 c/s to about 18 kc/s, the high upper limit resulting from the use of double-cone loudspeakers. Inside the coil of the loudspeakers is a fixed short-circuited ring, which virtually eliminates the self-inductance of the coil, so that the impedance rises only very little with the frequency. The amplifier feeding the installation should have a low internal resistance, which can be achieved by voltage feedback. Amplifiers type AG 9000 and AG 9006 are very suitable in this respect.

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 the Philips Research Laboratory, Eindhoven, Netherlands.


General remarks on the state of fundamental physical research in Europe and elsewhere. The author discusses some of the conditions under which research is pursued, its changing background and organization, the problem of language and the present shortage of theoretical physicists in Europe. The article concludes with some remarks on the aims and responsibilities of physicists.


Arc welding in a CO₂ atmosphere can be used on various types of mild steel, including (according to the investigations reported here) rimmed steel, provided that the consumable electrode contains sufficient de-oxidizing elements. The remarkable transfer of the droplets across the arc has been studied using a high-speed camera. Because the whole CO₂ welding process is chemically relatively simple, quantitative measurements can be made from which a good picture is obtained of the various reactions. It was found that welding in CO₂ is about "equivalent" to welding in argon + 9% oxygen, with the exception of the reaction which takes place with carbon. During welding, about 2% CO does not react with the oxygen from the air (calculated on the CO₂ being used). The main features of CO₂ arc welding are: absence of hydrogen, low nitrogen content of the weld, less trouble with the arc length in comparison with argon, very deep penetration which shows a U-form. Because of the latter feature unbevelled butt welds can be made with low heat input and low wire consumption. CO₂ arc welding can be performed more easily by machine welding than by hand welding, mainly because of the remarkable metal transfer, the very short arc and the high travel speeds.


Television, which is primarily an electronic technique, has caused a renewed interest in optical problems. It has led to a demand for certain optical systems: Schmidt systems, variable-focus lenses and dichroic mirrors are examples. Television optics has introduced a new stimulus into the already existing question as to how to judge the performance of an optical system. Finally television techniques may provide new tools for optics.


Although the regular-solution model is only an approximation, it may yield useful semi-quantitative results in predicting the form of ternary miscibility gaps from binary data: The spinodal equation of quaternary regular solutions has been derived and the coordinates of second-order critical points are given as a function of the six binary interaction parameters. Quaternary critical points are of special interest, as they are connected with closed miscibility gaps. The conditions which cause a ternary critical temperature to be raised by the addition of a fourth component are given. The results are applied to miscibility gaps in liquid and f.c.c. alloys.
Letter in which the author discusses and supports the plea of Oelsen, Schürmann and Heynert for thermodynamical analysis by purely calorimetric methods. Some extensions of this idea are put forward.


Continuation of **R 298.** In section 4 of this paper it is shown that the voltage dependence of the emittance is due to the presence of a Mott-Schottky barrier and may be expressed by 

\[ H = H_0 \exp \left( -\frac{V}{V^*} \right) \]

A theoretical model is drawn up for crystals embedded in a dielectric. This is tested against a number of experimental results reported in section 5 of the paper. Finally a study is made of the energy efficiency of electroluminescent phosphors.


The results of loss measurements at low temperatures on a number of glasses are given. These are discussed qualitatively in connection with the glass structure. The importance of impurities in fused silica is shown. The influence of thermal treatment is also considered. Contrary to experience with quartz crystals, no effect of irradiation (formation of colour centres) upon the dielectric losses at low temperatures is found. A comparative survey of the various loss mechanisms found hitherto in the vitreous and crystalline states is given.


After an electrolytic capacitor, e.g., Al/Al₂O₃/electrolyte, has been charged and discharged, a voltage is found to develop anew across the capacitor plates. This is called the residual voltage, and it is found to be proportional to the product of the field strength in the oxide layer and the thickness of this layer. It is assumed that Al³⁺ ions in the lattice have moved to adjacent positions, considering the fact that there is a large number of vacancies in the Al₂O₃ lattice. A simple computation shows that for an average shift of an Al³⁺ ion over a distance of 2 Å, 0.1% of the available Al³⁺ ions have been displaced.


Crystals of KCl and NaCl, coloured additively and quenched from high temperature to liquid-nitrogen temperature, show the F-absorption band and when irradiated in this band an emission in the infrared. If kept for a short time at room temperature a new absorption band (M-band) develops and irradiation in this band gives rise to a new emission band. If an M-absorption band is present, this new emission band is also found when the crystal is irradiated in the F-band. An explanation for this is offered. After long periods of ageing, R-bands also develop; irradiation in the R-bands as well as in the F-band gives rise to a third emission band.


Brief note announcing the attainment of \((BH)_{max}\) values up to 11 million gauss oersteds at a remanence of 11800 gauss and a coercivity of 1315 oersteds in permanent magnets of "Ticonal" X (titanium-containing), by preparation in an atmosphere of pure argon, using very pure raw materials. Rods of these alloys produced by pulling from the melt contain large crystals with a [100] axis nearly parallel to the direction of pulling, and a subsequent heat treatment in a magnetic field produces the high values reported above.

**R 305:** J. D. Fast: The influence of impurities on the recrystallization texture of cold-rolled 3% silicon iron (Philips Res. Rep. 11, 490-491, 1956).

In the preparation of grain-oriented silicon-iron sheet, whereby a preferred direction of magnetization is obtained by combined rolling and heat-treatment, the results are often poorly reproducible. The present note refers to an investigation which shows that the grain-orientation effect is brought about by impurities: the effect cannot be obtained in very pure silicon iron. It has been found that, in particular, small amounts of nitrogen introduced into the alloy before the cold-rolling produce a very good and reproducible texture. To achieve the optimum magnetic properties, the nitrogen must be expelled during a final heat-treatment.