THE PRINCIPLE OF THE MAGNETIC RECORDING
AND REPRODUCTION OF SOUND

by W. K. WESTMJZJE.

The hysteresis and non-linear character of ferromagnetism would appear to render the magnetic recording of sound a hopeless task. Despite these difficulties, sufficiently faithful recordings were accomplished as early as 1907 by pre-magnetizing the tape. Nowadays, the same result is obtained by superimposing an HF alternating current on the signal current. For a correct application of this principle, a careful study of the magnetization process of a magnetic tape is required. Such an investigation is described here, covering the recording and reproduction processes themselves, the frequency characteristic, distortion, noise, and other phenomena which influence the quality of the reproduction. The conclusion from this work is that magnetic recording not only competes successfully with other sound-recording methods, but may even surpass them.

Introduction

The nature of the processes involved in the recording and reproduction of sound on a ferromagnetic tape will first be discussed. The apparatus (fig. 1) and some properties of the ferric oxide coated magnetic tape have been discussed in an earlier publication 1). It was there pointed out that the material of the tape should have a certain remanence and not too low a coercive force, and consequently must show a certain degree of hysteresis. Special measures are then necessary to ensure linearity, i.e. to ensure that the resultant of two or more superimposed signals will be solely the sum of these signals.

Fig. 1. Schematic representation of a tape-recorder. M1 supply reel, M2 take-up reel, B magnetic tape, K1, K2, K3 erasing, recording and reproducing heads. A drive capstan, R rubber pressure idler, Gi and G2 idlers.

The process of magnetization as it occurs in the material of the tape will first be examined with the aid of a schematic representation. Next, the recording and erasing of signals will be discussed. Other matters to be dealt with include distortion (non-linearity between magnetization and signal strength), the reproduction process, the frequency characteristic, noise and the “print” effect.

Finally, the merits of the magnetic recording process will be compared with those of other methods of recording sound.

Schematic representation of the magnetizing process

As a rule, when working with ferromagnetic substances, a distinction should be made between reversible processes (in which the magnetization closely follows the field intensity), and irreversible processes. With small variations in the intensity of the external field, the magnetization is practically reversible. Irreversible changes occur when the variation in the field intensity exceeds a certain limit. Localised sudden changes — Barkhausen

1) D. A. Snel, Magnetic sound recording equipment, Philips tech. Rev. 14, 181-190, 1953 No. 7; hereafter referred to as I.

2) In a material uniformly magnetized by a solenoid, the induction B is composed of two parts:

\[ B = \mu_0 H + J. \]

In this \( \mu_0 H \) represents the contribution of the magnetic field of the current and \( J \) (the magnetization, i.e. the magnetic moment per unit of volume; \( J = \mu_0 M \)) the contribution of the material (B and J measured in Wb/m², H and M in A/m). The same formula is valid at every point of a piece of material of any given form, whether or not it has been placed in a magnetic field:

\[ B = \mu_0 H + J, \]

where B, H and J represent, respectively, the induction vector, the field vector and the magnetization vector, at any point in the field. In general the magnetic field is built up from various contributing elements:

\[ H = H_e + H_m, \]

\( H_e \) representing the external field, originating in electric currents or other magnets, and \( H_m \) the field of the “magnet poles”, which, due to the magnetization, occur on the surface and at discontinuities in the material.

In the case of a toroid \( H_m = 0 \). In other cases, \( H_m \) and J are usually in opposite directions and, since a decrease of \( \mu_0 H \) gives a greater decrease of B, the magnetization J will be smaller than it would be if \( H_e \) only were active. This is known as demagnetization. It should be borne in mind that the induction lines are always closed lines, as the induction B is subject to the law:

\[ \text{div} B = 0. \]
jumps — then occur in the various domains. When the field intensity changes in the opposite direction the magnetic processes will again be at first reversible and then irreversible. In general, the critical field intensity will have different values for various elementary domains of the material. The resultant hysteresis loop (figs 2b and c) is obtained by superposition of the magnetization curves of the various domains (fig. 2a). This complicated behaviour may be represented \(^3\) by the idealised magnetization curves of figure 3, which are built up of two fixed irreversible branches, connected by two (less steep) reversible branches. The slope of the latter corresponds to the initial permeability (fig. 3).

Comparison with fig. 4 shows that the real magnetization curve possesses the same character, apart from the rounding off of the sharp edges.

\(^3\) A similar procedure was followed by H. Toomin and D. Wildfeuer (Proc. Inst. Rad. Engrs. 32, 664, 1944).

**Recording method**

In the magnetic recording of sound, the tape — consisting of a homogeneous magnetic material or a carrier coated with magnetic material — is passed across the gap of the recording head (fig. 5). This consists essentially of an electro-magnet, the magnetic field of which, within certain limits, may be assumed to be proportional to the energizing current. The latter is derived from the original signal via an amplifier.

The intensity of the magnetic field of a “ring-shaped” recording head is at its peak value in the gap, where, however, it cannot be used. The active portion of the field is the stray field, in the vicinity of the gap. It decreases rapidly in intensity in the lengthwise direction of the tape and in a direction perpendicular to the tape (i.e. the direction of the thickness). If, for example, the recording gap has a length \(^4\) of 10 μ, it may be assumed that the

\(^4\) The “length” of the gap in this type of recording head is defined from the lengthwise direction of the tape. The “width” of the gap corresponds to the width of the tape.
effective field extends only some tens of microns from the gap. Consequently, when using a homogeneous tape of thickness say, 60 \( \mu \), only a layer of about 15 \( \mu \) facing the head will be magnetized.

Starting with a demagnetized tape, no permanent magnetization will be imparted to it unless the field strength of the applied signals is greater than a certain critical value \( H_{cr} \). This may be seen from the schematic magnetization curve of fig. 3. (In fact, there will be a very small remanent magnetization.) Only when the peaks of the signal field exceed the critical value \( H_{cr} \) will the magnetization change, say, from \( O \) via \( A \) to \( B'' \) (fig. 6), and from there fall back to \( R'' \), rendering the tape permanently magnetized. Evidently the remanence \( OR'' \) is not now proportional to the value \( H \) of the signal field, but to \( H-H_{cr} \), with the result that the signal is badly distorted.

The result of the recording of a sinusoidal signal of a low frequency and gradually increasing amplitude would be as represented in fig. 7.

Of course, the distortion could be diminished by the use of a material with a lower coercive force. However, as pointed out in article I, a certain coercive force is needed to prevent distortion of the

Fig. 5. Recording head. a) A core of laminated soft iron \( (K) \) with a very short air gap \( (S) \). This creates a stray field (dotted lines) around the gap. The tape \( (B) \) is carried across this gap and every particle traverses this stray field, the intensity of which increases when approaching the gap and decreases after passing the gap.

b) enlarged drawing of gap with tape.

For a coated tape, there is therefore no point in making the coating thicker than 15 \( \mu \).

When a particle of the magnetic material moves past the recording head, it is exposed to a magnetic field varying from point to point as regards intensity and direction; in general it will also vary with respect to time. For simplicity, we will first confine ourselves to the case where the frequencies of the signal are so low that during the time that a particle is exposed to the active field, the signal field is independent of time. With a tape speed of 0.7 m/sec and an active area of 50 \( \mu \), giving a transport time of about \( 10^{-4} \) sec, this condition will be satisfied when the frequencies are lower than 1000 c/s.

Fig. 6. If the material is exposed to a strong field which first increases and then decreases, the reversible portion \( OA \) is first described and then the loop \( BCDF \). If now the field starts to decrease when the point \( B'' \) is reached, then \( B''C'' \) is described. A similar effect is obtained for a negative field after it has reached its largest value, say, at \( D' \) (line \( D'F' \)).
sound track by stray fields and to counteract the influence of demagnetization in regions of sharp changes in the magnetization (i.e. small wavelength, corresponding to high frequency).

One solution of the linearity problem which has been used from the early days of magnetic recording is as follows. Before the tape is carried past the recording head, it is exposed to a direct field of such intensity that it becomes saturated and, consequently, when passing the head, it is in the state $R_v$. A direct current is now superposed on the signal current of such strength that the point $A$ would be reached if no signal were present. In this case, on leaving the region of the head, the remanent magnetization is proportional to the signal field; if this is zero, the tape again becomes unmagnetized. Linearity can indeed be obtained by this method, and usable records can be made. However, the noise inherent in tape that has gone through this cycle is much stronger than that of a virgin tape. The causes of this phenomenon will be given later when discussing the problem of noise.

Modern methods do not make use of a direct field; nowadays an alternating field is superimposed on the signal, of such a frequency that several cycles occur during the passage of the tape through the active portion of the stray field round the gap.

Assuming again a transport time for the tape of about $10^{-4}$ sec, it is clear that the frequency of this biasing field should be higher than $10^4$ c/s. In practice a much higher frequency is used, in the ultrasonic region, in the neighbourhood of $10^8$ c/s, so as to avoid the disturbing effects both of this frequency itself and of audible beat-tones between signal and biasing currents.

The amplitude of this field will, of course, vary in the length direction of the tape. If this field alone is applied, a particle arriving at the gap will first be taken through several hysteresis cycles of increasing amplitude until it is saturated, and will then go through a number of diminishing cycles, so that it is demagnetized as it leaves the head. (fig. 9). This process occurs whether tape was previously magnetized or not, and is put to use in the erasing head.

Consider the case when the high-frequency alternating field is superposed on the relatively steady signal field of the head. Now the positive and negative peaks of the field are not situated symmetrically with respect to zero field, but are symmetrical about the field corresponding to the signal. If the amplitude of the alternating field is now decreased below the critical value $H_{cr}$, the magnetization process again becomes reversible, although these reversible states are not represented on a line through the origin but on a line parallel to that line (fig. 10). For simplicity, suppose that only the amplitude of the alternating field decreases as the tape moves, the signal field being substantially constant: then the remanent magnetization will be that corresponding to the signal field and this will remain even when, finally, the signal field, too, is removed. The final state is such that when all fields have been removed, a remanence $R'$ remains.

---

5) V. Poulsen (inventor of the magnetic recording method, see 1) and P. O. Pederson, U.S. Pat. 873083, 1907.
The essential principle of the process is, therefore, the reduction of a hysteresis loop to a single reversible branch inside that loop. This transition takes place when the amplitude of the high frequency field (i.e., the difference in the value of $H$ at points $B'$ and $D'$, fig. 10) is exactly equal to $2H_{cr}$. The average value of the intensity of the signal field at that moment is the determining factor of the resulting remanent magnetization. This remains true though in reality its intensity changes at the same rate as the intensity of the alternating field, as the tape passes through the recording head. It is irrelevant that the signal field is not constant with time but is really a relatively slowly alternating field.

Distortion is inevitable when the signal current is so strong that a higher field exists than that corresponding to the maximum remanence of the material ($R$, fig. 3). Consequently, care must be taken that the signal strength does not exceed a certain level.

Distortion may also arise due to the demagnetization effect of adjacent parts of the tape. Consider, for example, a sinusoidal signal; if the positive peaks give rise to a magnetization directed to the right, the magnetization corresponding to negative peaks will be directed to the left (fig. 11). At the point under consideration, the oppositely directed magnetization in adjacent domains generate a field that tends to weaken the magnetization, especially when maxima and minima are close together (corresponding to shorter wavelength, i.e., higher frequency) and when the magnetization is strong. The relation between this demagnetizing field and the magnetization causing it, is represented in fig. 12 for a fixed, low frequency, by the line $I$.

**Fig. 10.** Recording using a high-frequency biasing field. A rapidly alternating biasing field is superimposed on the constant field $S$. The positive peaks are always higher than the negative ones. When the biasing field has reached its maximum positive value in $B'$, the cycle $B' C' D' F'$ is traversed. If the amplitude of the biasing field falls below the value $H_{cr}$, the magnetization remains on the reversible branch through $B''$; consequently, after taking away the biasing and signal field, the remanence $R'$ remains.

The remanence is always determined by the mean value of the two extreme field intensities (equal to the signal field) when the difference between them is exactly equal to twice the critical field intensity. This situation arises immediately after the gap has been passed, when the particle has already entered the decreasing part of the strong field: the above value of the remanence is now recorded on the tape.

**Distortion during recording**

It is clear that owing to the introduction of the HF biasing field, the remanence has become proportional to the intensity of the signal field because the irreversible branch is represented by a straight line, and all reversible branches are parallel to each other. Thus the distortion occurring in the absence of the biasing field has been eliminated in principle. A certain amount of distortion still remains, however, due to various causes.
When it has left the head, the part of the tape under consideration then attains a state corresponding to point $R_0$. As long as the reversible branches intersect the line $I$ at points within the hysteresis loop, the proportionality between signal and remanence is not impaired, not even when the demagnetization is diminished due to the magnetic "short-circuiting" effect of the soft iron of the reproducing head (as a consequence of this, the line $I$ in fig. 12 is replaced by a line with a steeper slope).

The proportionality is lost, however, when the intersection point would lie outside the hysteresis loop. In fig. 12 this is the case when, at higher frequencies, the demagnetization is represented by the line $II$. This causes a shift of the remanence from the line $R'R_0$ to the line $R''D''$.

Optimum value of the biasing current

As is evident from the above, the linearity is influenced by the magnitude of the biasing current as well as by the strength of the signal. If the biasing current is zero, the magnetization is zero until the signal field $H$ exceeds $H_{cr}$; it then increases in proportion to $H - H_{cr}$, until saturation is reached. This is the large distortion mentioned in the beginning, which occurs when no biasing field is used. In that case the signal is recorded on the tape a little further on, at the point where the biasing-field amplitude is exactly equal to $H_{cr}$. The more intense the biasing field, the further away from the gap this occurs and the weaker, at a given signal current, the operative signal field. The more intense the biasing field $H_b$, the more it must decrease to reach the value $H_{cr}$. The signal field must suffer a corresponding decrease; hence, for a given signal current, the remanent magnetization decreases as the biasing current increases.

These conditions are represented in fig. 13a. As the curvature of the line representing magnetization as a function of signal field is a measure of the distortion, it is clear that with weak signal currents, the distortion decreases with increasing biasing current ($H_b$). For strong signal fields, however, (depending on the exact values) the distortion first decreases with biasing field and may then suffer an increase due to saturation, followed by a further decrease. With average signal strengths the behaviour lies between those stated above.

In practice, a value of the biasing current is chosen such that it corresponds nearly to the secondary maximum for strong signals. This is a compromise, adopted because, as will be seen later, a higher value of the biasing current must be avoided, whereas with lower values, distortion may occur owing to the fall off in intensity of the field for particles furthest from the tape surface.

Effect of the biasing current on the frequency characteristic

The sound signal is recorded on the tape at the moment when the intensity of the biasing field is equal to $H_{cr}$; in practice, the value of $H_{cr}$ differs...
slightly for different particles, so that there is a spread of the critical biasing field, and the signal is not completely recorded until the lowest value of the critical biasing field is reached. The position and the length of the recording zone of course depend on the strength of the current producing the biasing field. If during the recording of a rapidly alternating signal the value of the biasing field does not decrease quickly enough, it is possible that a part of the tape, after having passed the spot in which the intensity of the biasing field is exactly equal to the critical value, is brought again on the irreversible branch by the rapidly increasing signal field. This may cause a false rendering of the signal. The higher the signal frequency, the sooner this result is to be expected, because in that case the signal field, when passing the above-mentioned zone, changes in intensity more rapidly. This false rendering results in a certain attenuation of the recording of the high frequencies.

There are other and more important consequences of the differing coercivities among the particles of the tape. Two particles at the same spot on the tape but with different $H_{cr}$ values will not record the signal at the same moment and therefore will record a different phase. This phase shift of the signals on the sound track results in "interference attenuation" at high frequencies.

At a given biasing current, the points where $H = H_{cr}$ will not lie on a plane perpendicular to the tape, but on a curved surface. Consequently, particles with the same $H_{cr}$ but situated in different depths of the tape will meet the critical field intensity at different distances from the gap. This also makes the phase shifts of the recorded signal dependent on the depth in the tape. During reproduction, it is precisely those particles which lie instantaneously on the plane of symmetry of the gap which produce the signal, so that the summation of the out-of-phase signals again results in attenuation of the higher frequencies.

If the biasing current is stronger, the region where $H \approx H_{cr}$ lies farther away from the gap and is more extended. In this case the attenuation is noticeable at lower frequencies.

The distortion caused by demagnetization, mentioned earlier, which becomes worse with increasing frequency, can also attenuate the high frequencies, for, owing to this distortion, not only are the higher harmonics superposed on the fundamental, but the fundamental is itself attenuated.

It should be noted that the schematic representation of the magnetization process which has been used in this article, is only an approximation and cannot adequately explain every detail. To go into further detail would be to go beyond the scope of this article 6).

The reproduction process; influence on the frequency characteristic

In order to convert the magnetic pattern on the tape back into an electrical signal, the tape is carried past the reproducing head, the construction of which is similar to that of the recording head (fig. 14).

Fig. 14. Reproducing head $K$ with winding $W$, gap $S$ and screening $A, B$ represents the magnetized tape. The lines of force are indicated schematically.

Considering an arbitrary cross-section of the tape, the recorded magnetization $J$ gives rise to a total magnetic flux $\Phi$. As the lines of magnetic induction are always closed, they must close outside the tape, so that an equal and opposite flux is found there.

When the tape makes contact with the head, the lines of induction will close mainly via the material of the head (owing to its high permeability) and so link the reproduction coil. Thus a flux flows through this coil, which to a first approximation is equal to the flux traversing the cross-section of the tape facing the gap. When the tape moves on, changes of this flux induce the signal voltage in the coil. Due to the good magnetic conduction of the iron circuit, whereby the demagnetizing field is reduced, the flux mentioned is even greater than it would be with a tape moving freely in the air.

The closer the tape comes into contact with the head, the more will the demagnetizing field be reduced. If the surface of the tape is not completely smooth it will be in true contact with head only at certain points. In this case, the demagnetizing field is not completely removed, and at small wavelengths a decrease in the magnetization will occur. This decrease will be greater as the slope of reversible branches becomes steeper (and thus the reversible permeability greater).

It should be noted, however, that not all the induction lines will enter the pole pieces and hence do not all link with the coil. One reason for this is that the magnetic resistance of the iron circuit can never be quite zero, so that small magnetic potential difference will always remain across the gap, and as a result, a flux proportional to this potential difference will pass across the gap. Therefore it is desirable to have a gap with a magnetic reluctance that is high compared with that of the iron circuit, i.e. a "long" gap with the small "height" \( h \).

Taking into consideration constructional demands, namely the mechanical strength of the poles, the machining precision and the duration of life of the head, the height of the gap has been reduced as far as possible. It should be borne in mind that during use, the tape is moving continuously across the head at a high speed and with a fairly high pressure and that the magnetic particles of the tape are in fact a form of the well-known polishing agent jeweller's rouge. The resulting wear reduces the height of the gap to such an extent that after say, 500 hours, the head must be exchanged. The life time of the head of course also depends on other details of its construction and on the quality of the tape used.

A large gap length cannot be used, however, for more fundamental reasons: while it is true that for long wavelengths practically all lines of force emanating from the tape enter the poles and link with the coil, this is no longer true when the wavelength is comparable to the gap length. This occurs at relatively low frequencies if the gap length is large. In this case a large number of the lines of force do not enter into the poles at all, but close through the air of the gap (fig. 15). To a first approximation this can be expressed as follows: the flux through the coil (gap length = \( l \), wavelength = \( \lambda \)) is approximately proportional to

\[
\frac{\sin (\pi l/\lambda)}{\pi l/\lambda}
\]

For small values of \( l/\lambda \), i.e. if \( l \geq \lambda \), this expression is practically equal to unity and independent of \( \lambda \). With higher values of \( l/\lambda \), i.e. at high frequencies, the value of the expression decreases and with it the frequency characteristic. If \( \lambda = l \) and consequently \( l/\lambda = 1 \), the expression = 0 and no flux at all flows through the coil. Therefore the gap must be shorter than the smallest wavelength essential for reproduction.

A second cause for the lines of force not linking with the head lies in the fact that at very long wavelengths (fig. 16) the lines of force take a path around the head, especially so when it is surrounded by the inevitable shielding (\( A \)). Supposing now that only the lines of force over a certain length \( L \geq l \) of the tape contribute to the flux through the coil, the flux becomes proportional to:

\[
\frac{\int_0^L \sin (2\pi x/\lambda) dx}{2\pi} = \frac{\lambda}{2\pi} [1 - \cos (2\pi L/\lambda)].
\]

This means that for wavelengths \( \lambda \geq L \) only a negligible part of the flux traversing the tape at the point where it faces the gap, enters the coil. As the wavelength decreases, a maximum is reached for \( \lambda = 2L \), and with still shorter waves, maxima and minima (= zero) would alternate for \( L = (n+1/2)\lambda \), and \( L = n\lambda \), respectively, in which \( n \) represents a whole number. This is not so serious as it sounds, because the transition between the flux making its way through the coil and the flux taking other paths is not sharp but gradual, which
results in the maxima and minima being smoothed to a considerable degree, making them imperceptible for \( \lambda \leq L \). Consequently, the result of this effect is mainly a decrease in the useful flux for wavelengths greater than \( L \) (fig. 17).

![Fig. 17. The form of the useful flux \( \Phi \) (in dB) as a function of the wavelength at long wavelengths. \( \Phi \) is plotted against \( L/\lambda \) (thus the frequency increases from left to right). If \( L = 25 \) cm and the speed of the tape = 0.76 m/sec, the maximum at the left corresponds to a frequency of 37 c/s.](image)

In general, the decrease of the useful flux at short wavelengths is more serious than at long wavelengths. The frequency at which this decrease occurs can in principle always be raised by increasing the speed of the tape. In practice the tape speed is increased to such a value that the remaining frequency correction can be successfully applied in the amplifier, without introducing too much noise and other disturbances. On the other hand, the amount of tape used becomes larger and the playing time decreases when the speed of the tape is increased. Moreover, the decrease of the useful flux at longer wavelengths, which corresponds at small speeds of the tape with frequencies below the audible range, is noticed as an irregularity in the characteristic and as an attenuation at lower, audible frequencies. It will also be seen below, that at higher tape speeds the "print-effect" becomes stronger at higher frequencies (and consequently becomes more disturbing). On account of this it is necessary to choose a tape speed which is a compromise between the reproduction of the high frequencies and the objections just mentioned.

**Overall frequency-characteristic: "transimpedance"**

In the preceding section the influence of the recording and the reproducing process on the frequency characteristic have been discussed separately. In practice it is difficult to separate the one influence from the other, as the magnetization brought about by the recording process can be measured only with a reproducing head. The voltage generated at the reproducing head can then be measured as a function of the current sent through the coil of the recording head. If we assume that this current is a pure sinusoidal current the relation between the voltage and the current mentioned can be determined as a function of the frequency \( f = \omega/2\pi \). This relation has the dimensions of an impedance and may therefore be called the "transimpedance".

If it is desirable to study the influence of one of the components of the system — recording head, tape or reproducing head — separately, this can only be carried out by relative measurements, which means that one of the components should be replaced by a corresponding part and a comparison made between the transimpedance measured before and after the exchange.

Ideally, i.e. excluding very low and very high frequencies, the transimpedance increases linearly with the frequency. It is therefore comparable with the impedance of an inductance.

The transimpedance depends not only on the frequency but also on the number of turns of the coils of both heads. Within certain limits we have a free choice in these, and thus the value of the transimpedance can still be varied at will.

Sometimes it is useful to consider, apart from the transimpedance \( Z_{18} \), another quantity which it is convenient to call the "transfactor" \( T \), defined by the relation:

\[
T = \frac{Z_{18}}{(Z_1 Z_2)^{1/3}}.
\]

\( Z_1 \) is the impedance of the recording head, \( Z_2 \) that of the reproducing head.

This factor is dimensionless, and is independent of the number of turns of the coils. In the ideal case it is a constant, independent of the frequency (fig. 18), of magnitude about 0.01.

![Fig. 18. Corrected frequency-characteristic (flux \( \Phi \) through the reproducing head) for tape velocities of 19, 38 and 76 cm/sec resp. At the same time the curves approximately represent relative values of the transfactor as a function of the frequency \( f \).](image)
Noise

Ground noise

The magnetic layer of a recording tape is built up from very small particles. If the layer is examined under an electron microscope, the size of the particles (fig. 19) is found to be about 0.1 μ. Now we can assume that every particle still contains some Weiss domains, separated by walls. If the tape is completely demagnetized, the fields of the Weiss domains will largely compensate each other, but still a weak, multi-polar field will emanate from every small particle. As a result of this, some lines of force will leave the material and create a micro-field, which irregularly changes its sign along the tape. This micro-field is easily detected by running the tape across the reproducing head, with its narrow gap of 10 μ. If then, a demagnetized or virgin tape is carried across the reproducing gap, it will continuously induce low irregular voltages into the coil of the head, which, after amplification, are audible as noise, the ground noise. This noise limits the weakest signal still reproducible and determines in that way the “dynamic range”. By this we understand the difference in level, measured in dB, between the largest signal which can be recorded without appreciable distortion and the smallest signal still audible above the ground noise.

In general, the more particles available to record the signal, the larger the dynamic range. If the average size of the particles is 0.1 μ, and the tape velocity is 0.76 m/sec, with a tape of width 6.3 mm and a magnetic layer thickness of 15 μ, the number of particles passing the gap per second will amount to about $10^{13}$. A simple calculation of probabilities shows that in the frequency range $0 < f < 10^4$ c/s the dynamic range will be at least 90 dB (in reality, due to partly unknown causes, about 70 dB is usually measured).

Modulation noise

A magnetized tape possesses more noise than a clean tape. It is true that this higher noise level is partly masked by the signal, but it is still audible, especially when the signal consists of a single note (pure sine function), which now sounds somewhat harsh. In order to understand this extra noise, it is necessary to consider the structure of the tape. The particles of the magnetic material are not evenly distributed through the carrier, but are grouped in clusters (fig. 19). In the demagnetized state, in every cluster the magnetic moments of the separate particles are irregularly distributed. In the magnetized state, in every cluster a more or less evenly directed magnetization of the particles is present. Due to the distance between the clusters and due to the fact that each cluster now represents a dipole, there is more chance that lines of force from the microfield will emerge outwards. This may also be expressed in the following way. Due to the grouping of the particles in clusters, the sensitivity of the tape shows fluctuations over long distances as well as short ones 7). This causes the signal to be multiplied by a factor which is a function of the point $x$ on the tape. If we call this factor $1 + δ(x)$, it is found that $δ(x)$ irregularly changes its polarity, even in an interval comparable with the smallest wavelength which can be registered. Still another way of expressing this would be to say that an interference signal $S(x)·δ(x)$, proportional to the signal, is superimposed on the signal $S(x)$. The noise caused by this is called the modulation noise. The ratio of signal/modulation noise is about 40 dB.

The measuring of the modulation noise is carried out by passing a direct current (in addition to the biasing current) through the recording head, equal

---

7) Fluctuations in the thickness of the magnetic layer, which may occur up to 1%, have the same effect.
in amplitude to the maximum admissible sinusoidal signal, and to measure the voltage induced in the reproducing head. Clearly a D.C. magnetization of the tape should always be carefully avoided, as the modulation noise of this D.C. magnetization would always be present. This magnetization may be caused, for example, by a permanently magnetized recording head, or a D.C. component of the biasing current. Even if the biasing current does not contain a D.C. component, it can cause D.C. magnetization, viz. when the positive and negative peaks differ in height. This is a result of the specific property of the tape to react only to the peaks of the magnetic field. It can now also be understood why the Poulsen method of using a D.C. biasing field may cause a higher noise level in the tape, especially in the weaker passages. This noise would not arise if the opposing field could exactly eliminate the D.C. magnetization; incomplete compensation, however, leaves a remanent magnetization in the tape. The advantage of the application of an HF biasing field is that, when no signal is present, the tape is automatically left in the demagnetized state.

Print-effect

If the magnetic material really behaved as suggested by the scheme given in fig. 3, only exterior fields of higher intensity than the critical value would be able to affect the recording. Such a strong field will not readily occur accidentally under ordinary circumstances. If appears, however, that weak fields, e.g. those originating from an adjoining layer in a rolled tape, may also influence the magnetization. Consequently, if parts of a tape carrying a very weak part of the recording happen to lie near parts where a sudden strong signal occurs, a part of the magnetization due to the latter signal may be transferred to the adjacent layer. In this way the strong signal may be weakly audible during reproduction once or even a number of times, before and after the real signal. This is the so-called “print-effect”. The transfer of magnetic energy is here effected by the thermal agitation. For the reversal of the magnetization of a Weiss-area, a certain amount of energy $E$ is required. Till now we have considered only the case when this energy is completely supplied by an exterior magnetic field. It can, however, also be supplied partly by the thermal agitation. The probability of a transition from one orientation to another as a result of the thermal agitation is given by the well-known expression $\exp(-\Delta E/kT)$, where $\Delta E$ represents the energy required for the transition, $k$ the Boltzman constant and $T$ the absolute temperature. When an equilibrium has set in, a weak field, in itself not strong enough to supply the energy for reversing the magnetization (i.e. roughly speaking, smaller than the local coercive force) may still cause a shifting of the equilibrium with the aid of the thermal agitation. After the interfering field has been removed the area does not resume its original state, at all events, not at once. It appears that the print-effect, as would be expected on this theory, strongly increases with increase of temperature, and is also dependent on the duration of the influence (it increases almost linearly with the logarithm of time, (fig. 20). When the field is removed it decreases again, but it does not disappear completely, as there will be some particles in such a stable state that it is highly improbable that they will return to their original state by the thermal agitation.

It will be understood that stray AC fields can also take over the part played by the thermal agitation and may cause an increase of the print-effect. With the aid of a high-frequency A.C. field it is even possible to transfer the recording from one tape to another in contact with it. In this way contact copies can be made 8) in a manner similar to photographic processes.

The print-effect is not equally strong for all wavelengths. The magnetizing field is in reality the field of the neighboring layer, the distance between this and the magnetized layer being equal to the thickness of the tape. The intensity of this field decreases exponentially with the ratio of the tape thickness ($d$) to the wavelength ($\lambda$), but it is also proportional to the ratio $d/\lambda$, in which $d$ represents the thickness of the magnetic layer, which is not-

---

mally smaller than \( \lambda \) (fig. 21). This is expressed in the formula

\[
\mu_0 H = \frac{\pi d}{\lambda} \cdot B_0 \cdot \exp\left(-\frac{2\pi \lambda}{\lambda}\right),
\]

where \( B_0 \) represents the average induction in the magnetized layer. The formula shows that the strength of the field has a maximum value when \( \lambda = 2\pi \lambda \). When the thickness of the tape \( \lambda = 55 \mu \), this maximum is reached for \( \lambda = 350 \mu \), with a tape speed of 0.76 m/sec. corresponds to a frequency \( f = 2200 \text{ c/s} \). This frequency is lower at smaller tape speeds, so that the audibility of the print-effect is then less.

**Comparison of the magnetic process with other recording methods**

In comparison with other sound recording and reproducing methods, the magnetic process has both its advantages and its disadvantages.

At the speeds used for professional purposes, i.e. at a tape speed of 30°/sec = 0.76 m/sec, the quality of the sound reproduced is superior to that of all other systems, thanks particularly to the favourable signal/noise ratio, which is perhaps equalled by that of a newly cut lacquer disc. The dynamic range of the gramophone records commercially available and of the optical systems (photographic and Philips-Miller processes) is certainly smaller.

Since, in optical processes, the number of electrons emitted by a photo-electric cathode is of the same order of magnitude as the number of magnetic particles passing the reproduction head per second in the magnetic process, it might be expected that the two systems would exhibit roughly the same dynamic range. However, the number of electrons emitted is not the only factor which influences the dynamic range in optical processes. The noise in optical systems is also dependent on a variety of other causes, e.g. the grain of the film and small irregularities in the film.

Another advantage of the magnetic process lies in the fact that both the negative and the positive magnetization contribute to the recording, which makes the "zero track", necessary in optical recording, superfluous. This eliminates the noise generated by a zero track, and at the same time, the necessity to suppress the zero track during weak passages ("noiseless reproduction").

Magnetic recordings are free from noise caused by dust particles, an additional source of noise found in all other systems. Dust particles are normally non-magnetic, so they do not contribute to noise in the magnetic process.

On the other hand, disturbing magnetic fields may unfavourably influence the magnetic recording, especially as regards the print-effect, which is not present in other recording processes. For some purposes the fact that the modulation is not visible may be a disadvantage. Nevertheless, the magnetic process is being used more and more in studios for broadcasting, and as an intermediate link in the gramophone and film industries.

The simple handling, during both recording and reproduction, is an important feature. This is especially important for the recording process, where, in all other systems, an expert technician is needed. The door is thus opened to a large number of amateur or semi-professional applications, at home, in the office, and for studying music or languages. The simplicity of the apparatus makes a compact construction possible, a very important feature for designing portable equipments.

A unique advantage of the magnetic process lies in the fact that a recording can be erased and a fresh one recorded at once. This has considerable economic advantages in some applications, and also
opens the door to a number of quite new possibilities, e.g. the magnetic recording of data in the “slow-memory” of modern computing machines. In this way intermediate results may be stored until needed for further computations.

As a tape is used in the magnetic process, it is very suitable for stereophonic recordings. This is also the case with the optical and with the Philips-Miller systems, but it is more difficult to achieve with the gramophone record. The two sound tracks necessary for stereophonic reproduction can be recorded side by side by using a double recording head (fig. 22) and similarly reproduced later on.

Summary. The processes occurring during the magnetic recording and reproduction of sound on a ferromagnetic tape are discussed in detail with the help of a simplified representation of the hysteresis loop and of the magnetization process in the iron-oxide particles of the tape. Linearity between signal and magnetization is attained by the application of a high-frequency biasing field. The strength of the biasing field influences both the linearity of the signal and the frequency characteristic. Distortion and attenuation of the high frequencies during recording may also be caused by demagnetization processes. Deviation from the flat characteristic during reproduction occurs with long waves (low frequencies) as well as with short waves (high frequencies). In the latter case, the tape speed together with the length of the gap of the reproducing head determine the highest frequency which can be reproduced. When further discussing the total frequency characteristic, it is useful to introduce the concepts “transimpedance” and “transfactor”. The noise of the tape is determined largely by the grain structure. An additional noise (modulation noise) sets in during magnetization, as a result of fluctuations in the thickness of the magnetic layer and the grouping of the magnetic particles into clusters. The transfer of magnetization to another tape is sometimes useful (for copying purposes), and at other times deleterious (print effect).

A comparison of the magnetic recording process with other recording processes shows that the quality of sound reproduction of the magnetic process is superior, in many respects, to others. Moreover, the specific qualities of this system (easy handling, erasure) favour its use in many applications.