Determining the Magnetization of Magnetic Tape*

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0 SYMBOLS USED FREQUENTLY

f	=	Frequency of recording
ω	=	Angular frequency, $= 2\pi f$
v	=	Tape speed in recording and reproduction
λ	=	Wavelength of recording, $= v/f$
w	=	Width of track
t	=	Coating thickness
Ω	=	$\omega t/v = 2\pi t/\lambda$
μ	=	Reversible permeability of coating (approximately equal to initial permeability)
l	=	Gap length of head
B	=	Rms surface induction
B_x	=	Surface induction at point x in tape
B_ω, B_λ	=	Rms surface induction at frequency ω or wavelength λ
Φ	=	Rms tape flux
Φ_ω	=	Rms tape flux at frequency ω
Φ_0	=	Rms tape flux for $\omega \to 0$
$\hat{\Phi}$	=	Peak value of tape flux.

1 MAGNETIZATION

As we will show, it is not possible to give an exact specification of the magnetization (or the magnetic polarization) of a magnetically recorded tape as a single number without specifying the measuring conditions. A magnetic tape shows the same fundamental characteristics as any other permanent magnet. For example, the air gap induction that is attainable depends on both the magnetization and the reluctance of the magnetic circuit. The magnetization of a magnet would be defined by the B–H graph. However, it is constant only along the region of the solid line in Fig. 1, in which it is also characterized adequately by the induction B_{roc} or the impressed magnetomotive force H_i and by the slope of the shear line, the reversible permeability μ_r. With a knowledge of the geometric relationships of the magnetic circuit, the induction to be expected (for example, in the air gap of a loudspeaker or a measuring instrument) can be determined mathematically with an accuracy usually sufficient for practical purposes. Since, however, permanent magnets are almost always made and magnetized for a specific use, knowledge of the induction in the air gap B_{oc} suffices.

2 SURFACE INDUCTION

With magnetic tape one may distinguish two (or really three) conditions: on the one hand, the "open-circuit" condition, when the tape is in free space (this condition also approximately obtains when the tape is wound on a reel) and, on the other hand, an essentially "short-circuit" condition, when the tape is in contact with a (usually highly permeable) head. Schematically these conditions can be represented by the two points B_{rsc} and B_{roc} in Fig. 1. In practice, however, the coating is not magnetized uniformly throughout its thickness, so that one can only give an average value of the magnetization. Instead of this, however, one can indicate directly the surface induction of the tape in either the open-circuit or the short-circuit condition. As can be demonstrated

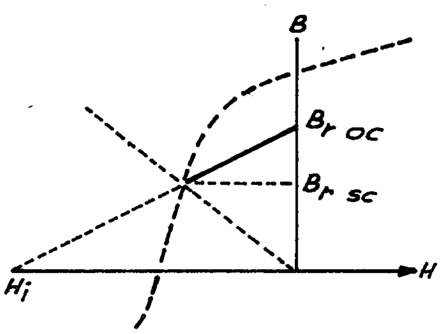

Fig. 1. Demagnetization graph for a permanent magnet.

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[1], [2], the conversion between these two conditions entails a relationship involving the recorded wavelength and also the thickness and permeability of the coating, so that besides the surface induction (be it in the open-circuit or the short-circuit condition), thickness and permeability must be specified in addition to the wavelength.

The open-circuit surface induction can be determined by measuring the emf induced in a single conductor, across which the tape to be measured is pulled [3], [4]. Because of the extraordinarily small induced voltage, and the influence of the geometric dimensions of the conductor, this measurement requires great care. Hence its use remains limited to a few research laboratories.

Since the normal operating condition of the tape is doubtless that of contact with a high-permeability reproducing head, the short-circuit surface induction should be taken as the appropriate quantity.

3 TAPE FLUX

Here a short intermediate consideration should be introduced. With sufficiently long wavelengths, a recording made with constant signal current versus frequency will produce a remanent induction on the tape that is independent of frequency (wavelength). Consequently the remanent flux Φ_ω in the tape will also be independent of wavelength. This has been verified experimentally (see [5, sec. 6]). The relationship between the surface induction and the flux in this case is

$$wB_x = \frac{1}{2} \cdot \frac{-t}{dx} \hat{\Phi}_0 \cdot \cos \frac{\omega}{v} x = \frac{\omega}{v} \cdot \frac{\hat{\Phi}_0}{2} \cdot \sin \frac{\omega}{v} x$$

$$B_\omega = \frac{\omega \cdot \Phi_0/2}{vw} = \frac{\pi \Phi_0}{w\lambda} .$$

The surface induction is thus inversely proportional to the wavelength when the magnetization is constant. Hence it is more suitable to specify either the short-circuit flux or the short-circuit flux per unit of track width, rather than the surface induction, as the measure of the magnetization. Short-circuit flux may sometimes be abbreviated to simply "tape flux."

Whereas the short-circuit surface induction is not accessible to a direct measurement, the measurement of a very long-wavelength tape flux can be referred to the measurement of the flux in a tape magnetized with zero frequency, that is, for a recording wherein the audio signal current is replaced by an equivalent direct current. This process has been described in [6] and has also been accepted as a German standard [7]. In the present paper the possibilities for errors appearing in this measurement will be discussed. Therefore we will first review the process briefly.

4 MEASUREMENT OF TAPE FLUX

The tape whose flux is to be measured (say, the reference level section of the DIN test tape) is reproduced on whatever equipment is available, and the output voltage E_h from the reproducing head is measured. Then the same frequency is recorded on a blank tape, and the signal current I_{ac} is adjusted to give the same reproducing head output voltage E_h as before. Next an equivalent dc magnetization is made on the same blank tape by feeding the recording head with a direct current I_{dc} equal to the rms value of I_{ac}. One must make certain that the bias current remains unchanged.

From the tape so recorded, n pieces (about 30–50), about 200–300 mm long, are packed together to form a bundle, which is then held together with some pieces of pressure-sensitive tape (splicing tape). This bundle is, as it were, a "flexible bar magnet": the flux of the bundle Φ_b can be measured magnetometrically [6] or with a fluxmeter.[1] The flux on the tape Φ_t is then

$$\Phi_t = \frac{\Phi_b}{n} .$$

With this method, several points must be considered in order to avoid possible errors:

1) Permanent magnetization of the head, asymmetry of the bias current, and nonerasable magnetization on the blank tape can all cause errors in the results. In order to eliminate this source of errors, one prepares two bundles of tape having reversed polarities of the direct current. The desired tape flux is then equal to the arithmetic mean value of the values measured with these two bundles.

2) Nonlinearity, especially due to overrecording or because of too small a bias current, can cause an error in determining the equivalent direct current I_{dc} because the distortion can give an incorrect reading of the reproducing head voltage E_h and consequently incorrect values for I_{ac}. The influence of this source of error can be reduced to a negligible value if one selects a blank tape such that less than 1% distortion occurs for the necessary recorded flux. If necessary one may record a lower flux and correct the measured result according to the reduction in the recording.

3) There may be a "frequency response" error at the frequency or wavelength used. One may make an estimate as follows. With a homogeneously magnetized coating, the drop in flux with frequency follows the relationship[2]

$$\Phi_\omega = \Phi_0 \cdot \frac{\tanh \Omega}{\Omega} \cdot \frac{\mu + \tanh \Omega/2}{\mu + \tanh \Omega} = \Phi_0 \cdot f_1(\Omega, \mu) .$$

[1] Since the flux of the bundle is very small and the sensitivity of the ballistic galvanometers or fluxmeters usually available is low, the usual measuring accuracy is low. An electronic fluxmeter was therefore developed by RTI; see Section 9.

[2] *Editor's note*: This is identical to Westmijze's eq. (8) [1, p. 261], with the tape-to-head spacing (Westmijze's a) = 0. Schmidbauer's Ω is Westmijze's kd, where k is the wavenumber $2\pi/\lambda$ and d is the coating thickness (see sec. 4.6 in J. G. McKnight, B. Cortez, and J. A. McKnight, "Tape Flux Measurement Revisited," *J. Audio Eng. Soc.*, vol. 46, this issue).

With $t = 12\ \mu m$, $v = 380$ mm/s, and $\omega = 2\pi \times 1000$ Hz, $\omega t/v = \Omega = 0.2$, so that with a permeability of $\mu = 2.5$, a drop of 5% will already occur. One must then count on a measurement uncertainty of this order of magnitude. Since the loss—expressed in percent or decibel—is approximately proportional to the frequency and to the coating thickness (or the depth of penetration of the magnetization), it can be decreased by the use of a lower frequency for the reference level—say about 500 Hz—and a tape with a sufficiently thin coating, or a low bias so that the coating is only magnetized part of the distance through. The bias current should not exceed that required for maximum sensitivity. This mode of bias conforms with that for the next section.

5 DETERMINING THE PERPENDICULAR COMPONENT OF THE MAGNETIZATION

The magnetization of the tape may be assumed to be longitudinal, as a first approximation. If, however, one chooses a bias current greater than that for maximum sensitivity, then the perpendicular component contributes more and more to the total tape flux, especially at the tape surface [8]. With the measurement of the flux by the fluxmeter method, only the longitudinal component of the magnetization is detected. Although the magnetometric method measures the perpendicular component properly, this measurement method is unwieldy. One would therefore try to make the perpendicular component as small as possible from the beginning.

The detection of a perpendicular component, and the estimation of its magnitude, may be performed with an Oersted meter, such as that devised by Förster, or other similar apparatus (for example, an electron-beam head [9]) that was calibrated with the aid of a tape, which was itself calibrated by the magnetometric method [6].

The following process was devised by RTI. Two 200–300-mm-long pieces of the dc magnetized tape to be measured were held togther temporarily by means of splicing tape. A spacing of about 2–3 mm was left between the ends of the tapes, and the flux induced into the measuring gap due to this spacing was determined. It is clear that in this arrangement the fluxes originating from a transverse magnetization and flowing in the measuring gap cancel mutually, as shown in Fig. 2. Now one piece is removed from the splice and instead fastened with the coating side against the splicing tape, again with a 2–3 mm spacing. When this "one-half inverted" sample was again placed on the measuring gap, the flux originating from a perpendicular magnetization causes the measured flux to be larger or smaller. The difference is therefore a measure of the perpendicular magnetization. It can be shown by using this method that the perpendicular component assumes substantial relative values only with biasing currents that are considerably greater than those required for maximum sensitivity, I_{b0}. Since the vectorial sum of the components is measured in reproduction [1], a perpendicular component that does not exceed 10% of the longitudinal component may be neglected, since the error then remains less than 0.5%.

6 MEASURING TECHNIQUES SUMMARY

Summarizing the requirements for accurate tape flux measurement, a blank tape with the least possible sensitivity variations should be used. (This is important for the accurate determination of I_{ac}.) A thin coating and the highest possible flux should be used, as well as a bias current that gives about maximum sensitivity.

When possible, use a test frequency for which the wavelength loss should be negligible. This can be confirmed by measuring the frequency response of the recording with a reproducing head whose output voltage is measured through an integrating amplifier (that is, an amplifier whose response is inversely proportional to frequency, with no other "equalization"). Note that at long wavelengths, the wavelength is comparable to the dimensions of the reproducing head (head face length, length of contact between tape and head face, and size of shields). At these wavelengths the reproducing head has an appreciable wavelength response, and that response must be taken into account.

The measured result is then defined as the "tape flux." The weber [Wb] is the SI unit. With multitrack recorders, or with magnetic film, the tape flux per unit of track width is more useful, thus the weber per meter [Wb/m].

According to German standard DIN 45 513, the following values are used for the tape flux of the DIN reference level section of the various DIN test tapes:

Test tape for 760 mm/s, at 1000 Hz, 1.00 nWb per 6.3 mm = 160 nWb/m.

Test tape for 380 mm/s, at 1000 Hz, 2.00 nWb per 6.3 mm = 320 nWb/m.

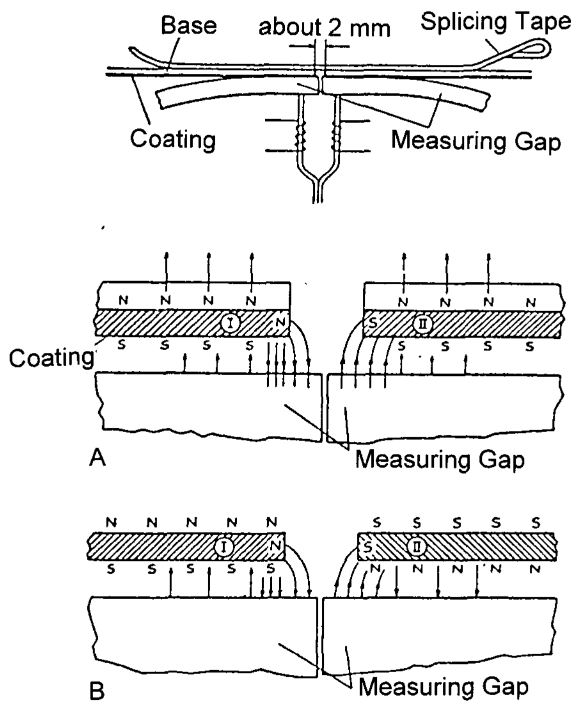

Fig. 2. Method for determining the perpendicular component of the dc magnetization.

Test tape for 190 mm/s, at 333 Hz, 1.60 nWb per 6.3 mm = 260 nWb/m.[3]

Test tape for 95 mm/s, at 333 Hz, 1.60 nWb per 6.3 mm = 260 nWb/m.

For broadcasting purposes, however, at the 190-mm/s tape speed, a value of 2.00 nWb (= 320 nWb/m) has been chosen for the tape flux for the "maximum recording level" at 1000 Hz. When the standard flux versus frequency curve used in Germany is considered,[4] the tape flux at lower frequencies is seen to be 2.36 nWb, which is thus about 3.3 dB above the (then) standard value of 1.6 nWb. This value was chosen in consideration of the requirements for recording on magnetic film, in particular the magnetic sound tracks at the edge, in order to achieve a sufficient signal-to-noise ratio.

Comparisons of systematic "round robin" measurements were carried out by several research and industrial laboratories. These found an agreement between the measured results to within a fraction of a decibel.

7 THE "EQUIVALENT NUMBER OF TURNS"

With the aid of the DIN reference level section of a DIN test tape, which has been calibrated by the methods described, the sensitivity of any reproducing head can now be calibrated. In any head, a division of the tape flux takes place: part of the flux threads the coil (the useful flux), and part is shunted directly across the gap and lost as far as the coil goes. It is practically impossible to calculate the reluctances accurately. Therefore the efficiency of the reproducing head must be determined experimentally.[5] In practice, the flux sensitivity itself is of little value. We are interested instead in the product of the sensitivity and the number of turns of the coil, since this product determines the emf induced across the coil. Thus it is more useful to indicate the equivalent number of turns, which may be calculated from the reproducing head emf E_h produced by the tape flux Φ_0 from the DIN reference level section at the frequency f by the equation

$$N_{eq} = \frac{E_h}{2\pi f \cdot \Phi}.$$

For example, if $E_h = 3.14$ mV, $f = 1000$ Hz, $\Phi/w = 320$ nWb/m, $w = 6.3$ mm, so $\Phi = 2.00$ nWb and then $N_{eq} = 250$.

Unfortunately the equivalent number of turns on a head is not constant because the shunt reluctance of the gap decreases through wear of the head face in the course of use; therefore N_{eq} increases. A reproducing head thus cannot be used for a long time as a calibration standard.[5] (A paragraph on the "Electromagnet K10" has been omitted in this translation.)

8 MEASUREMENT OF THE TRANSVERSE MAGNETIZATION (PILOT SIGNAL TRACK)

(This section, which contains Figs. 3 and 4, has been omitted in this translation.)

9 ELECTRONIC FLUXMETER

An electronic fluxmeter was developed by RTI. It consists of an induction coil with a calibrating coil and an electronic integrator,[6] as shown in Fig. 5. When a magnetized sample is pulled out of the coil, a voltage impulse is produced at the coil terminals, according to Faraday's law: $E = n\, d\Phi/dt$. Therefore the flux is $\Phi = n \int^t E\, dt$.

The first amplifier stage (an EF 804 pentode vacuum tube with a 10-MΩ input resistance and a capacitive negative feedback from plate output to grid input) is an integrator. Two integration time constants are available: range 1, 5 s, and range 2, 2.5 s. Since the length of the coil is only 18 mm, and the test bundle is pulled out at a speed of at least 1000 mm/s, even in range 2 the integration error still remains less than 1%.

The second stage (another EF 804) provides voltage gain, driving one-half of an ECC 40 triode connected as a cathode follower. Because the first two stages are ac (capacitively) coupled, it is necessary to use a peak-holding detector. This is done by capacitively coupling the output of the cathode follower to the grid of the other half of the ECC 40, which is unbiased, and therefore acts as a rectifier and amplifier (a grid detector). The capacitor holds the peak value of the integrated pulse until it is discharged by pressing the "zero set" button. The ECC40 was chosen because it had the best insulation properties.

The plate current of this triode is measured by an ammeter with a full-scale sensitivity of 6 mA. After the "zero set" button is pressed, the plate current is adjusted to full scale (6 mA) by the 50-kΩ rheostat marked "CAL, 6 mA." After the end of the integrated impulse produced by withdrawing the tape from the coil, the charge remains on the capacitor for a long time. This causes the plate current of the tube to fall to a lower value, which is the measure of the flux. The meter pointer will oscillate for a moment, then come to rest. Then the meter reading can be taken.

If the sample were incorrectly poled, the meter would continue to show a full-scale reading after the sample was inserted. In this case you can press the "short input" switch while you throw the "reverse" switch to reverse the poling of the induction coil.

The power supply must be regulated since the indication depends on the plate voltage. There is an additional regulator for the first stage because of its sensitivity to power supply voltage changes.

[3] *Editor's note*: Changed in 1962 to 320 nWb/m at 1000 Hz.

[4] *Editor's note*: At that time, a transition frequency of 1600 Hz (time constant of 100 μs) was used at 190 mm/s.

[5] *Editor's note*: This statement is true for general-purpose heads, but not for a high-efficiency head designed especially for measurement purposes.

[6] *Editor's note*: The availability of inexpensive integrated-circuit operational amplifiers with very good dc stability (such as the Linear Technology chopper-stabilized LTC 1050) makes the construction of an integrator much simpler.

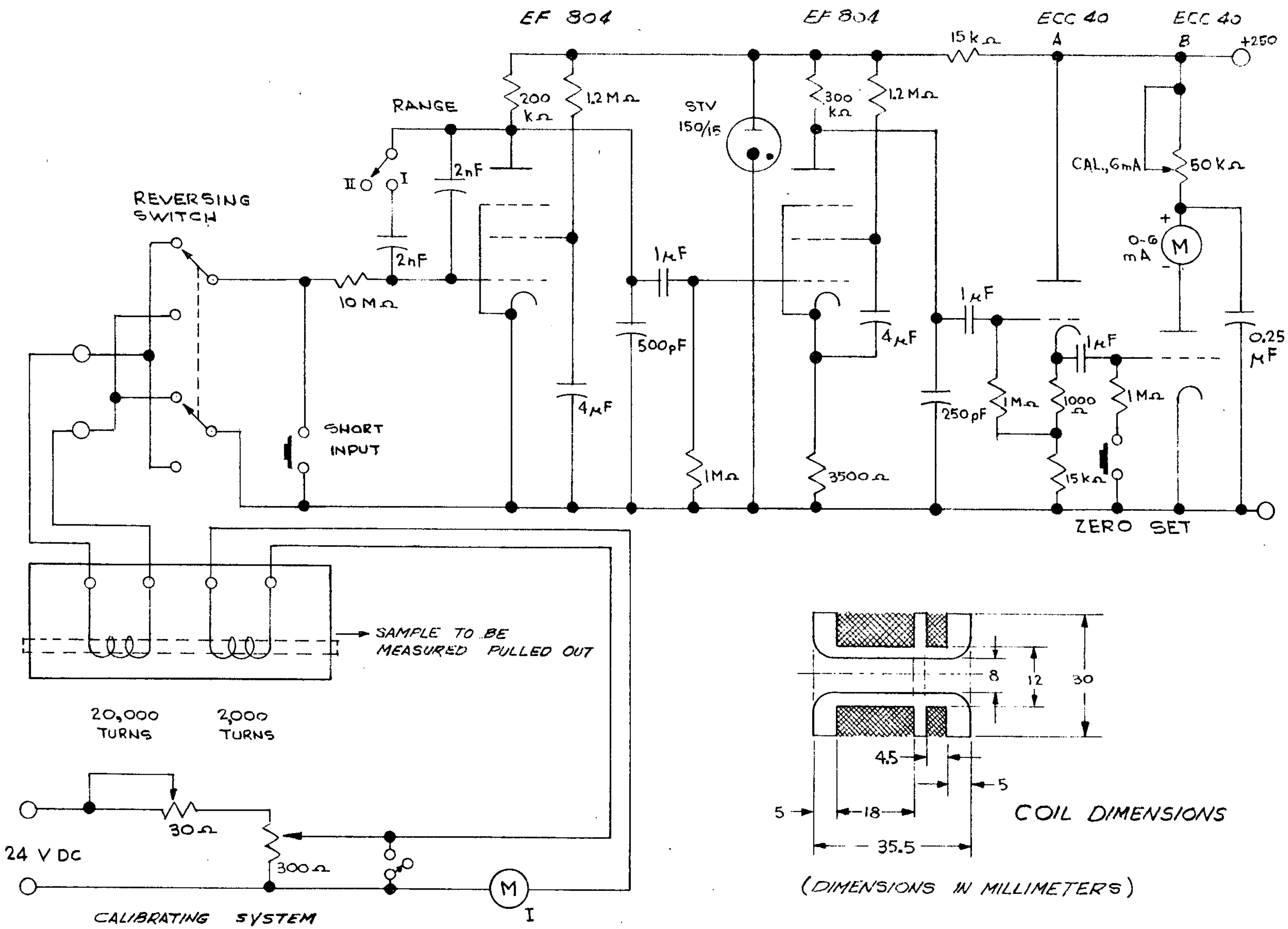

Fig. 5. Schematic diagram of electronic fluxmeter, circuit for calibrating it, and construction of induction coil.

In order to calibrate the apparatus, the main induction coil ($N_1 = 20\,000$) has an auxiliary coupling coil ($N_2 = 2000$). The mutual inductance was determined by the usual means[7] as $M = 108$ mH. A current change of ΔI amperes through the auxiliary coil hence corresponds to a flux change,[8] that is,

$$\Delta\Phi = \frac{M \cdot \Delta I}{N_1}[\mathrm{H} \cdot \mathrm{A}] = \frac{108 \times 10^{-3}\,\Delta I}{20\,000}[\mathrm{Wb}]$$

$$= 5.4 \times 10^{-6} \cdot \Delta I\,[\mathrm{Wb}]\,.$$

Each measuring range is calibrated by using several values of ΔI. When the calibration current switch is opened and closed, reversely directed current (and therefore flux) surges result. A test for the correct functioning of the meter is that after the switch is opened then closed, the meter must return to its previous reading.

10 REFERENCES

[1] W. K. Westmijze, "Studies on Magnetic Recording," *Philips Res. Rep.*, vol. 5, pp. 148–157, 161–183, 245–269, 343–366 (1953).

[2] O. Schmidbauer, "Das Feld des harmonisch magnetisierten Tonbandes: Die Abtastung im Leerlauf, bei idealem Hörkopf und bei extremer Spaltbreite" ("The Field of a Sinusoidally Magnetized Magnetic Tape: Reproduction in Open Circuit, with an Ideal Head, and with a Very Long Gap Head"), *Frequenz*, vol. 6, pp. 281–290, 319–324 (1952).

[3] E. D. Daniel and P. E. Axon, "Absolute Measurement in Magnetic Recording," Monograph 2, Engineering Div., BBC (1955 Sept.).

[4] R. Schwartz, I. E. Sheldon, and F. H. Comerci, "Absolute Measurement of Signal Strength on Magnetic Recording," *J. Soc. Motion Pic. TV Eng.*, vol. 64, pp. 1–5 (1955).

[5] O. Schmidbauer, "Zur Bestimmung des Frequenzganges von Tonband-Magnetisierungen" ("Determining the Frequency Response of the Magnetization of Magnetic Tape"), *Elektron. Rundsch.*, vol. 11, pp. 373–375 (1957 Dec.).

[6] H. Schiesser and O. Schmidbauer, "Beitrag zur Normung der Magnettontechnik" ("Contribution to the Standardization of Magnetic Sound Recording"), *Frequenz*, vol. 6, pp. 222–229 (1952).

[7] DIN 45 520, "Verfahren zum Messen von Absolutwert und Frequenzgang des remaneten magnetischen Bandflusses auf Magnettonbändern" ("Method for Measuring the Absolute Magnitude and Frequency Response of the Flux on Magnetic Tape"), German standard (1957 Sept.). In translation, *J. Audio Eng. Soc.*, vol. 46, this issue.

[8] J. Greiner, "Der Aufspeichervorgang beim Magnettonverfahren mit Wechselstromvormagnetisierung" ("The Recording Process in AC-Biased Magnetic Sound Recording"), *Wissenschaftliche Berichte, Folge III, Elektrotechnik.*, no. 6 (Verlag Technik, Berlin, 1953).

[9] A. M. Skellett, L. B. Leveridge, and J. W. Gratian, "Electron-Beam Head for Magnetic Tape Playback," *Electronics*, vol. 26, no. 10, pp. 168–171 (1953).

[7] *Editor's note*: I am aware of two means for measuring the mutual inductance between two coils. My guess is that Schmidbauer's "usual means" is to use an inductance meter to measure the inductance of the two coils under consideration, first in series aiding L^+, then second in series opposing L^-. Then the mutual inductance is $M = (L^+ - L^-)/4$. The other means is to treat the two coils as a transformer and to measure the input current i and frequency f as well as the open-circuit output voltage u. The mutual inductance is then $M = u/2\pi f i$). It does not matter which winding is used for input and which for output—the mutual inductance is the same.

[8] *Editor's note*: For an English-language reference, see F. K. Harris, *Electrical Measurements* (Wiley, New York, 1952). The section on galvanometer calibration (pp. 366–367) explains this general method for using a mutual inductor to calibrate any kind of search-coil fluxmeter.