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THE PERMEABILITY OF LAMINATIONS FOR MAGNETIC RECORDING AND REPRODUCING HEADS

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Although catalog values for the maximum permeability of head materials such as 4-79 mo-permalloy are about 300 000 μ_0, the practical values for initial permeability at 1000 Hz for thin laminations bonded together into a head core are more nearly 5000 μ_0 to 10 000 μ_0.

The initial permeability of a toroid or a "gapless" head may be calculated from physical dimensions and an inductance bridge measurement. The Maxwell bridge with a variable capacitance works especially well.

0 INTRODUCTION

basic effeciency of a magnetic recording-or reproducing-head is greatly influenced by the low-frequency permeability of the core material. The frequency response of these heads is influenced by the core permeability versus frequency, which may be called the permeability spectrum. The manufacturer's catalog [1] for the commonly-used 4-79 molybdenum permalloy gives the maximum permeability as 300 000 μ_0.[1]

Experience shows that this value is much greater than that actually obtained in the construction of magnetic heads--a permeability of about 5000 μ_0 to 20 000 μ_0 is usually found in practice. The first section of this paper briefly explains the reasons for this apparent discreapancy. These results can be used to give approximate permeabilities in the many cases where samples of the actual core material are not available. The preferred solution however is to measure the actual permeability of the material to be used in the design and construction of the heads. Permeability is calculated from measurements of the inductance of a coil wound on the sample and the mechanical dimensions of the sample. The second section of this paper discusses perparing the sample, measuring the complex inductance, and calculating the complex permeability.

WHAT IS A PRACTICAL VALUE OF PERMEABILITY?

The manufacturer's catalog value of maximum permeability of 300 000 μ_0 is reduced by the following factors:

[1]Permeabilities in this paper are given the form of a number times μ_0 where μ_0 is the permeability of vacuum, 1.25 microhenries per meter. The number (say 300 000) is the relative permeability. The products (say 300 000 μ_0 = 375 millihenries per meter) is the absolute permeability.

* Portions of this report are based on work the author performed when he was employed by the Research Department of Ampex Corp, in 1971.

1.1 Induction at which measurement is made. The maximum permeability value is reached at an induction of about 300 millitesles [mT]. The induction in the core of a reproducing head is in the order of 50 μT. The biasing field in a recording head is in the order of 30 mT. Thus the initial permeability (the value for an induction of about 1 mT of less) is the only significant value for head design purposes. For the material discussed here, the initial permeability is 30 000 μ_o as opposed to the maximum permeability of 300 000 μ_o, as is shown in Fig. 1, drawn from the manufacturer's literature [1]. Bozorth [2] shows this effect in his Fig. 5-48.

1.2 Thickness of the lamination. The initial permeability given above is for a lamination thickness of 350 μm (14 mils). For a more usual value of 150 μm (6 mils) for magnetic heads, the initial permeability drops to 25 000 μ_o [1]. Thornley and Kehr [3] show similar initial permeabilities for thicknesses of 100 μm through 12.5 μm, and a sharp decrease for thinner laminations of 6.3 μm through 2.5 μm as shown in Fig. 2. Peterson and Wrathall [4] show that in practice there are imperfections in the surfaces of the lamination. Thus thinner laminations are "more surface," and usually show even greater reductions in permeability with decreasing thickness than those reported here.

1.3 Frequency of the measurement. Because of eddy currents in the laminations, the complex permeability spectrum drops with increasing frequency [1],[2],[3],[4],[5]. The manufacturer's data [1] shows that the initial permeability drops from 25 000 μ_o at 60 Hz down to 15 000 μ_o at dc/at 800 Hz, for the 150 μm thickness lamination. The greater the initial permeability, and the higher the test frequency, the greater is the permeability reduction compared to the dc value. For the usually-assumed homomogemous laminations, the well-known formula for complex permeability vs frequency is given by Bozorth [2] and also, with a normalized graph, by Olsen [5]. In fact, most practical laminations have an appreciable surface layer of low permeability, as mentioned in Sec. 1.2 above. This surface layer causes a further decrease in complex permeability at higher frequencies. The theory, formula, and experimental verifications are given by Peterson and Wrathall [4]. Fig. 3 shows a typical complex permeance spectrum measurement.

1.4 Stress due to bonding laminations into a core. In order to obtain very high permeabilities, it is necessary to remove all stress in the material. The bonding of the laminations, however, re-introduces stresses. Known bonding materials will not withstand the temperatures necessary for re-annealing. Preece and Thomas [6] show permeability vs applied tensile stress, with a stress of 24 megapascals [MPa] dropping the initial permeability of a 100 μm thick sample, measured at 400 Hz, from about 50 000 μ_o to about 25 000 μ_o. Their graph is shown in Fig. 4. Finke [7] shows the effect of bonding 50 μm thick laminations of HyMu 80: the 60 Hz permeability drops from 40 000 μ_o to 25 000 μ_o; the 25 kHz permeability drops from 10 000 μ_o to 8 000 μ_o.

Scholz [8] shows the reduction of the initial permeability due to the contraction of the bonding material in making a core, from about 25 000 μ_o before bonding to about 12 500 μ_o after bonding.

Bendson [9], in his figure 1, shows that the permeability of a material with an initial permeability of 70 000 μ_o drops to 4100 μ_o when bonded; and one with an initial permeability of 11 000 μ_o drops to 3800 μ_o when bonded. Also, it appears that "hard" bonding materials cause greater permeability reduction than "soft" bonding materials.

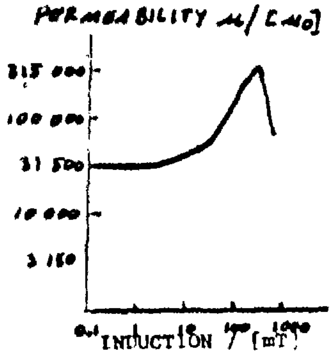

Fig. 1 μ vs induction.

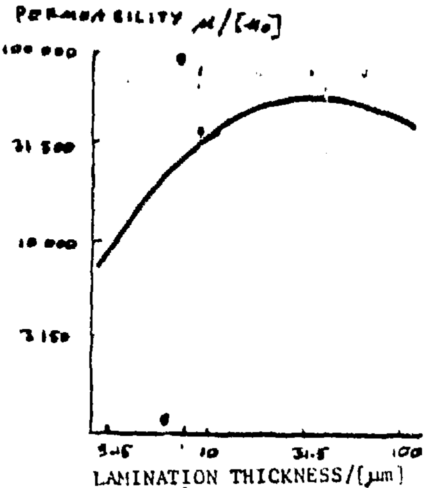

Fig. 2 μ vs lamination thickness.

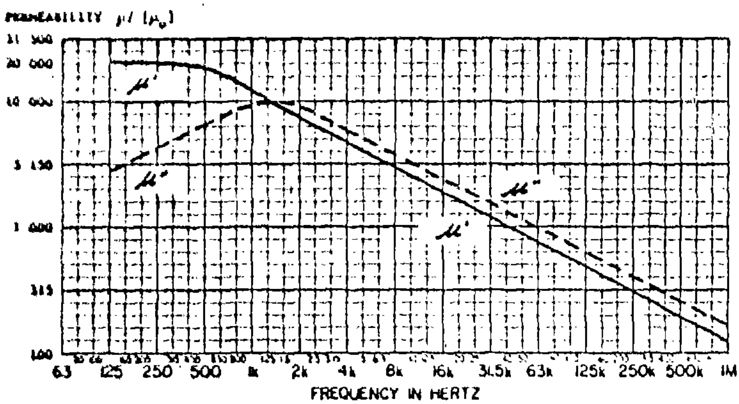

Fig. 3 TYPICAL MEASURED COMPLEX PERMEABILITY SPECTRUM, TOROID, LAMINATION THICKNESS = 165 μm

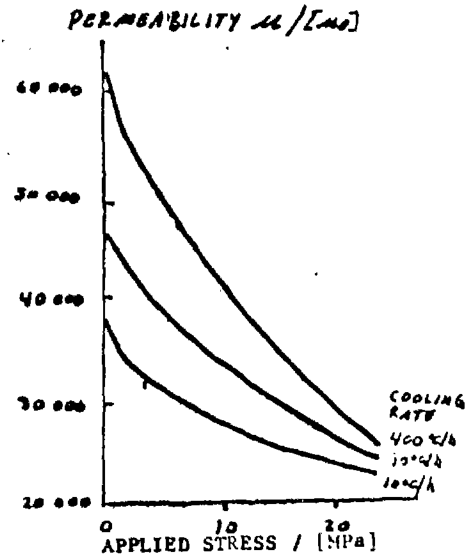

Fig. 4 μ vs applied stress.

1.5 Some conclusions on estimating or calculating a "realistic" complex permeability spectrum. Considering the above four factors, it is apparent that the manufacturer's catalog values of 100 000 μ_o to 300 000 μ_o have no practical value in head design calculations. Even when a troidal sample of the actual lamination is available, a measurement of the initial permeability of the unbonded sample at a single low frequency such as 60 Hz is probably of relatively little practical value.

A good estimated value of permeability at 1000 Hz for a well-made core seems to be about 10 000 μ_o. The use of a higher value in head calculations would have to be justified by actual measurements. Scholz [8] even suggests using 5000 μ_o as a typical value.

Finke [7] has pointed out that the high annealing temperatures (1120°C) usually used to obtain maximum initial permeability soften the material mechanically, causing increased difficulty in machining the heads, and perhaps causing increased rates of wear of the head by the tape. He proposes that, since the very-high permeabilities are not realizable in the bonded cores, it would be advantageous to use a lower annealing temperature of say 925°C or perhaps even 700°C for higher-frequency applications. Kehr [10] reaches similar conclusions.

Bendson [9] has recently described a very low-wear material with a dc permeability after bonding with a very hard material of 4000 μ_o. For the audio-frequency range, the complex-permeability spectrum of finished cores from this material compares very favorably with that for the traditional materials which seem at first glance to have so much higher permeability.

2 THE MEASUREMENT OF CORE PERMEABILITY

From the discussion in Section 1, it is apparent that a permeability measurement, to have any real validity, must be made at a low induction (1 mT or less); at a frequency of at least 1000 Hz, and preferably at the highest frequency at which the head will be used rather than just at 63 Hz (20 kHz for ordinary recording heads; and 1 MHz or higher for duplicator heads) and on laminations of the actual thickness to be used, bonded together in the same way that will be used for the actual head core.

The sensitivity, the frequency response, and the electrical impedance of a head depend on the complex ratios of complex quantities--the gap permeance is a real quantity if a non-conducting spacer is used, or a complex quantity if a conducting spacer, as shown by Otto [11]. The core permeance is always complex, as shown by Peterson and Wrathall [4] and Olson [5]. Therefore, accurate calculations of the head performance require the measurement of the complex permeability of the core permeability. Only rough approximations can be calculated from the more-commonly measured and specified modulus of the permeability.

Measurement of the inductance is always done by winding a coil on the sample, measuring the physical dimensions of the sample and the complex inductance (inductance L and resistance R) of the coil, and calculating the permeability from these measurements. When the sample of magnetic material is a simple closed path (in particular, a toroid), all of the permeance is in the magnetic material itself, and an accurate measurement of the performance of the magnetic material is possible. When there is an air-gap in the circuit, for instance, in a "head" which is assembled without a mechanical spacer between the poles, an unknown permeance is introduced by this air gap. The magnetic circuit will therefore have an apparent permeability which is less than the true permeability of the magnetic material itself. A correction for the gap permeance can be estimated, but the result is never more than a rough estimate.

The preferred method is therefore to make a test toroid at the time the cores are made, and measure the test toroid. If no toroid is available, as all too frequently happens, one must assemble two core halves with no gap shim, and calculate an approximate permeability.

2.1 Preparing the Sample.

2.1.1 Preparing a toroidal sample. In each batch of lamination punchings, or each fret of etched laminations, make a toroid. Heat-treat, then stack and bond the toroids in the same way that is used for the head cores themselves.

Next measure the thickness, and the inside and outside diameters of the toroid, in millimeters. For precision measurements, make a correction for the non-magnetic bonding material included in the thickness measurement. In practice, this correction is usually negligible.

Wind a layer of insulating tape on the toroid to prevent the sharp corners of the toroid from cutting the insulation on the winding, and making short circuits in the winding. Then wind a coil on the toroid. The coil must be distributed around the core evenly, and it should give an inductance which can be measured conveniently by the available inductance bridge. About 10- to 20- turns is often convenient. A larger wire size such as 1 mm diameter (AWG 18) reduces the dc resistance of the wire, but a smaller wire such as 0.5 mm diameter (AWG 24) may be easier to handle. A bifilar coil, made by forming the wire into a "hairpin" and winding the coil with double wire, is convenient for measuring the voltage for calculating the induction at which the inductance is measured. Finally the inductance is measured, as described in Section 2.2.

2.1.2 Preparing a "head" sample. In many cases completed cores are available, but no toroidal sample. In this case an approximate measurement of the permeability can be made.

Most head cores consist of a "body" of fairly large cross-section and length, and a "tip" of fairly small cross-section and length. In this case, the major contributors to the total reluctance will be the reluctance of the high-permeability core material of the "body", and the reluctance of the low-permeability gap at the tips. The gap is an unknown combination of actual air gap between the ends of the tips, and a layer of low-permeability magnetic material caused by the lapping of the tips. I have found that as this unknown gap is typically about 0.4 μm long, [12] and an approximate correction can be calculated based on this length. First measure the cross-sectioned dimensions of the body and the tips, and the length of the magnetic path, all in millimeters. Then lap the tips of the core to be flat and smooth as for manufacturing a head; wind on a layer of insulating tape, then wind 5- to 10-turns on each half-core. Then clamp the half-cores together, as though making a head, but with no gap spacer. Do <u>not</u> lap the "front face"--leave the tip depth as large as possible. Finally measure the inductance as described in Section 2.2.

2.2 Measuring the Complex Inductance. Measurement of the complex inductance (that is, the inductance and the resistance) of head lamination samples presents certain special requirements: a wide range of frequency of measurement (63 Hz or less, up to 250 kHz and sometimes 1 MHz or more); rapidity and ease of operation (thus is especially important when a permeability spectrum is needed), and a wide range of reactance to resistance ratio ("Q") measurement (Q from 0.05 to 100 is typical). Because of the process variations in the magnetic materials to be measured--especially in the heat treating and bonding--an accurate measurement of L and R, such as 1% or better serves little practical purpose. A medium accuracy of measurement, such as 10% to 20%, is more appropriate.

Measurements can be made with impedance bridges or with vector or complex impedance meters. Bridges are available from several makers for about $1000. Unfortunately, they are designed with limited flexibility, but for high accuracy. Terman and Pettit [13] in Chapter 3, "Circuit Constants of Lumped Circuits," point out that the Maxwell Bridge with a variable capacitor is particularly well-suited to measuring inductance of low- to medium-Q inductors: the balance equation is independent of the inductor losses and of the frequency, and the variable capacitor arrangement prevents any interaction between the resistance and reactance balances even at the lowest values of Q.

Unfortunately, this configuration is not commercially available, probably because of the high cost of a precision variable capacitor. For low to medium accuracy, you can "do it yourself", as described in the Appendix, which shows the circuit and the balance equations.

The commercially available bridges (Hewlett-Packard, GenRad, Heathkit, and others) all use the "variable-resistance Maxwell Bridge" Circuit. This bridge is very difficult or impossible to balance with low-Q inductances such as those discussed here, because the resistance and reactance branches of the bridge interact, and this produces a "sliding balance". Most of these bridges are designed for a single frequency (1000 Hz), with provision for an external oscillator covering up to 20 kHz or sometimes 100 kHz. The R-balance arm is usually calibrated to read Q at 1000 Hz, with some calculation necessary to find the actual value of R.

The "sliding balance" problem with this bridge configuration can be solved by several other approaches: One Hewlett-Packard bridge uses an automatic resistance-arm balancing system, but this only operates at a test frequency of 1000 Hz. One GenRad bridge uses a mechanical coupling between the R- and L— balance dials ("Orthonull") which greatly reduces the "sliding" effect.

Yet another type of complex-inductance measuring device is the "vector impedance meter" (Hewlett-Packard) and the "complex-impedance meter" (Dranetz Engineering Labs), which cost from 2000$ to 7000$. They have variable frequency, but still do not cover 63 Hz to 1 MHz in one instrument. Although they avoid the "sliding balance" problem, they use a phase-detection system, and the errors in their phase-detection systems are such that a resolution of the measured Z and θ, or X and R, into the desired L and R can only be achieved over a Q range of about 0.2 to 5. This severely restricts the usefulness of these instruments for the purposes here.

Thus if you are going to buy a commercial bridge or meter, be sure to actually try it out in your lab first with typical test toroids and heads; and expect to buy two bridges or meters to cover the total frequency range.

Some calculation, according the instrument manufacturer's instruction manual, is usually needed to convert dial readings of any bridge or meter into the desired L and R. A programmable calculator is a very great convenience for these calculations.

The complex inductance, and also the complex core permeability, may be expressed in terms of either the "series equivalent" or the "parallel equivalent" values, just as for lumped electrical circuit elements[14]. Each representation has its own particular advantages, but be sure not to mix them inadvertently. I have usually used the series-equivalent representation for head design work. Olsen [5] describes complex inductance and permeability, and the series-equivalent and parallel-equivalent forms in detail in his Chapters 4 and 5. He shows that:

$$L_p = L_s(1+1/Q^2)$$
$$R_p = R_s(1+Q^2)$$
$$\text{where } Q = \omega L_s/R_s = R_p/\omega L_p$$

The measured resistance of the coil includes the dc resistance of the coil itself. To determine the effective resistance due to the core material alone, the dc coil resistance must be subtracted from the series-equivalent total resistance:

$$R_e = R_s - R_{dc}.$$

Where R_e is the eddy-current resistance due to the core material, R_s is the measured series-equivalent resistance, and R_{dc} is the measured dc resistance of the coil.

2.3 Determining the Induction at which the Permeability is Measured. The induction at which the inductance is measured is easily calculated from the voltage across the coil during the measurement. In many cases, both terminals of the coil are "floating" in the inductance bridge; therefore an ordinary "one-side-grounded" voltmeter cannot be used. A differential meter could be used if one is available. It is usually simpler to wind a bifilar coil on the core (see Section 2.1.1 above), and measure the voltage across the terminals of this sensing coil.

For measurement purposes, we need to determine the sensing coil voltage U that corresponds to the desired induction:

$$U = 2\pi BANf$$

where B is the desired induction (usually about 1 mT) in teslas,
A is the cross-sectional area of the core in square meters,
N is the number of turns on the sensing winding, and
f is the test frequency in hertz.

Most bridges have a control for the test-signal amplitude; that needed for an induction of 1 mT is often at or below the lowest value at which the bridge will operate. Fortunately, the induction for the test is not critical, but it should not exceed 10 mT. (Note that for a fixed induction, the coil voltage will be proportional to the test frequency.)

2.4 Calculation of the Complex Permeability

Having measured the complex inductance values L and R, we first calculate the complex permeance (reciprocal reluctance):

$$P' = L/N^2 \quad [H]$$
$$P'' = R/(2\pi f N^2) \quad [H]$$

where N is the number of turns of the test coil, and f the test frequency.

Then from the complex permeance and physical dimensions of the specimen we calculate the complex permeability:

$$\mu'\mu_o = P'\ell/A$$
$$\mu''\mu_o = P''\ell/A$$

where A is cross-sectional area of the toroid, and ℓ is the path length, all in meters.

When the specimen is a toroid, we may use the exact formula for the ratio of ℓ/A :

$$\ell/A = 2\pi/[w \ln(d_2/d_1)]$$

where d_2 and d_1 are the outer and inner diameters in consistent units, and w is the width (thickness) of the toroid in meters.

A typical plot of μ' and μ'' has been shown in Fig. 3.

When there is a gap in the magnetic circuit--such as for the "gapless" head--the measured value represents a minimum possible value of permeability. An approximate correction may be made, to arrive at a better value of the permeability of the magnetic material itself:

$$\underline{P}_c = \underline{P}_m \underline{P}_g / (\underline{P}_g - \underline{P}_t),$$

where $\underline{P}_c$ is the true value of the complex permeance of the core material,
$\underline{P}_m$ is the measured value of the complex permeance of the "gapless" head, and
$\underline{P}_g$ is the estimated permeance of the gap, calculated from the measured cross-sectional area of the pole tips, and the estimated "gap length" of 0,4 µm.

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APPENDIX: A "DO IT YOURSELF" INDUCTANCE BRIDGE

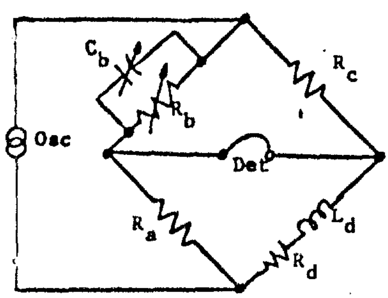
Considering the cost of commercial impedance bridges and meters, and the unavailability of a bridge or meter which truly suits the measurement requirements at hand, you might want to make up your own bridge from components and a standard laboratory oscillator and voltmeter.

The circuit and balance equation for an orthogonal (that is, non-sliding balance) Maxwell bridge are shown in Fig. A1. This variable capacitance form, which I have used, works very well.

n this circuit either the detector or the oscillator must be balanced. An oscilloscope with a differential input connection could be used for the detector. I have used an oscillator with a balanced output, the H-P Model 200CD. This oscillator has an unbalanced output attenuator which must be operated at the full clockwise (no attenuation) setting. A simple external balanced attenuator can be used to reduce the signal amplitude as necessary.

For 10 % to 20 % accuracy, which is usually sufficient for these measurements, an inexpensive capacitor box and resistor box (Heathkit and others) can be used. A 10-turn rheostat (Helipot) is also inexpensive and very convenient for R_b.

For greater accuracy, precision resistors and capacitors can be used. You would then also need to take care with shielding and grounding of the bridge, the effects of residual impedances, etc. See Terman and Pettit [13], Sections 3-4 and 3-5; and Harris [15], Chapter 15, "Alternating-Current Bridges".



BALANCE EQUATION:

$L_d = R_a R_c C_b$

$R_d = R_a R_c / R_b$

Usually $R_a = R_c = R$, so that:

$L_d = R^2 C_b$

$R_d = R^2 / R_b$

Fig. A1 Maxwell bridge with variable capacitor, to avoid sliding balance: Circuit and balance equations.