Tape Flux Measurement Revisited*

JOHN G. (JAY) MCKNIGHT, BENITO E. CORTEZ,** AND JEFFREY A. MCKNIGHT**

Magnetic Reference Laboratory, Mountain View, CA 94043, USA

Analog magnetic recording standards specify the recorded signal magnitude in terms of short-circuit flux per unit track width, called fluxivity. Two flux measurement methods are standardized: a direct ac method using a high-efficiency head (AES7/ANSI S4.6) and a transfer-to-dc method using a fluxmeter (German standard DIN 45 520). A transfer-to-dc measurement made in the 1950s is used to calibrate the fluxivity of German calibration tapes. When these tapes are measured by the direct ac method, the fluxivity is 10% less than the stated value. Thus the 1950s German transfer-to-dc measurement was 10% more sensitive than the direct ac measurement. A new comparison of the two measurement methods shows that they actually have the same sensitivity; the experimental error of our measurements is about ±1%. Thus we conclude that the German measurement in the 1950s must have had a 10% error, and that the fluxivity on all of the calibration tapes based on the old German measurement is 10% less than the stated value—tapes identified as 320 nWb/m are actually 288 nWb/m.

0 INTRODUCTION

The quantity used to express the magnitude of the recorded signal in analog magnetic recording is the magnetic flux[1] [1], [2]; the unit in the International System of Units (SI) is the weber [Wb]. For most purposes the magnetic flux per unit track width is more useful. We have coined the term "fluxivity" for this quantity. Its SI unit is the weber per meter [Wb/m], and a practical submultiple for tape recording is the nanoweber per meter [nWb/m].

Reproducer calibration test tapes contain a reference fluxivity section. Typical values of reference fluxivity are in the range of 100–500 nWb/m. The IEC standard for calibration tapes [3] mentions reference fluxivities of 250 and 320 nWb/m. This reference fluxivity section of calibration tapes is used directly to calibrate the sensitivity of heads and complete reproducers, and indirectly to calibrate the sensitivity of recorders and tapes. This facilitates both the practical exchange of tape-recorded programs with standardized recording fluxivities, and the interchange of information about the elements of the recording system. Therefore accurate and consistent fluxivity measurement is very important.

The most thorough early work on tape flux measurement was published by Schmidbauer [1] in 1957. That paper is timeless, but has not previously been available in English translation. We have now completed a translation of it, and that translation also appears in this issue.

The original standard for measuring tape flux was the German standard DIN 45 520, first published in 1957 [4]. It provides for two methods of flux measurement:

1) A transfer-to-dc measurement, wherein a dc recording is made having the same flux as the unknown ac recording. Then the dc flux is measured by one of several possible magnetometric methods.

2) A direct ac measurement using a reproducing head having a known sensitivity at a known frequency. In this standard the head for the direct ac measurement was calibrated by reference to the transfer-to-dc method, because no method was known at that time for an accurate direct calibration of the head sensitivity.

The direct ac and transfer-to-dc methods are reviewed in Sections 1 and 2 and summarized in Table 1.

Schmidbauer performed the original German research into tape flux measurement at the Rundfunktechnisches Institut, Nürnberg (RTI; now called Institut für Rund-

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[1] Some magnetic tape recording standardization work refers to the measurement of the tape "magnetization," but this is technically incorrect, as explained in the introductory parts of Schmidbauer [1]. Also, "it is not possible to measure directly the magnetization, M [amperes per meter], that actually occurs inside a recorded tape—one can only measure the flux (Φ) at the surface of the tape" [2, sec. 2.1]. Therefore such references to magnetization should be changed to "flux."

funktechnik, IRT). In practice, because it is very time consuming, the transfer-to-dc measurement is made only once, and from this a known ac flux is recorded. That recorded tape becomes the transfer standard for calibrating systems that in turn are used to produce commerically sold calibration tapes. Starting in the 1950s, the German tape manufacturers AGFA and BASF (now combined as BASF Magnetics) both produced calibration tapes based on the German transfer-to-dc measurement. We do not know who actually produced this German transfer standard for tape flux—whether the IRT, AGFA, or BASF. We do know, however, that calibration tapes from AGFA and BASF have had a consistent flux, and we will refer to this as the German flux measurement.

In the mid-1960s the first author (then working at

Table 1. Comparison of direct ac and transfer-to-dc methods of measuring medium-wavelength tape flux at 1000 Hz.

Direct AC Measurement		Transfer-to-DC Measurement	
Theory: Faraday's Law of Induction			
Φ	$= E/[n \cdot 2\pi f \cdot \eta_\Phi \cdot f(\lambda, f)]$	Φ	$= (\int^t E\,dt)/[n \cdot f(\lambda, t, \mu)]$
where		where	
Φ	= tape flux	Φ	= tape flux
E	= emf generated in a head with a coil of	$\int^t E\,dt$	= time integral of emf generated with a coil of
n	turns	n	turns
f	= frequency of reproduced signal	$f(\lambda, t, \mu)$	= response of recording and reproducing *process* (*not* reproducing equipment) as a function of wavelength, coating thickness, and tape permeability, between infinite wavelength of measured transfer dc recording and wavelength of ac tape flux whose value is to be determined
η_Φ	= flux efficiency of head		
$f(\lambda, f)$	= response of *reproducing head* as a function of wavelength (gap loss at short wavelengths, and head bumps and secondary gap effect at long wavelengths) and frequency (eddy current loss)		
Procedure for Use			
AC Flux Measurement: The unknown alternating tape flux at a medium wavelength is sensed by a special high-efficiency flux measuring head, whose calibration factors are known (number of turns n, wavelength and frequency response $f(f, \lambda)$, and medium-wavelenght absolute flux efficiency η_Φ). The head emf E and the frequency f are measured, and the flux is calculated from the above formula, the flux efficiency, and the head response.		*Transfer*: The unknown ac flux at a medium wavelength is sensed by a reproducing head whose emf is measured. Another recording of the same ac flux and frequency is made on a blank tape, and the rms ac recording current is measured. Then a recording of dc flux is made, using exactly the same blank tape and bias, and a dc of the same magnitude as the rms value of the previous ac. Because the recording system may have an unknown residual dc magnetization, the recording should be made in both polarities and the average taken. The bias current should be set for maximum recording sensitivity for the ac flux. (Overbias causes increased vertical flux; underbias causes increased distortion.) *Measurement of Wavelength Response of Recording and Reproducing Process*: The wavelength response between direct current and the medium wavelength is measured by a means not presently standardized. *DC Flux Measurement*: The dc transfer recording is cut into pieces whose length is about 100 times their width. A bundle of many layers is formed in order to increase the total flux to be measured. The total dc flux is measured with a sensitive fluxmeter, and the corresponding ac flux per layer is calculated from the above formula, the above wavelength response, and the number of layers in the bundle.	
Sources of Error			
The flux sensitivity of the head can be calculated, and several indirect measurements confirm the calculations. Comparison with the transfer-to-dc measurement proves the calculations.		There are changes of sensitivity of the blank tape over its length. The method of determining the recording wavelength response is not presently standardized, and there is no proven means of calculating the response accurately. The recording process will not be linear if the recording current is too great, or the bias current is too small.	
Special Equipment			
Calibrated high-efficiency flux measuring head that is wider than the tape. A calibrated integrating amplifier simplifies the measurements and reduces the measurement errors.		Recorder and reproducer with calibrated recording frequency response from dc to 1000 Hz. Recording and reproducing heads should be wider than the tape to avoid fringing. Signal generator with calibrated output voltage from dc to 1000 Hz. Blank tape with constant sensitivity versus length. Means to determine the wavelength response of the recorder and blank tape, from dc to 1000 Hz. Sensitive, low-drift fluxmeter.	

Ampex Corp.) developed a new way to calibrate directly the sensitivity of a reproducing head for use in the direct ac flux measurement [5]. But when he used this method to measure the flux recorded on German calibration tapes, he found a 10% (almost 1-dB) discrepancy (described here in Section 3), which persists to this day. The following possible causes were proposed for the discrepancy:

1) An error in the magnetic theory, wherein the two measuring methods—assumed to be equivalent—were not in fact equivalent

2) An error in the practical calibration or measurement using the direct ac method

3) An error in the practical calibration or measurement using the transfer-to-dc method

4) Some combination of these.

A review of the theory (see Section 3) showed that there is no error in the magnetic theory. Thus the first author believed that there must have been some error of practical calibration or measurement. One difficulty in finding this error was that by the mid-1960s the German transfer-to-dc measuring system, and the people who operated it, no longer existed. Another difficulty was that, although in [5] he had made a transfer-to-dc measurement, it contained an error in the wavelength response calculation [6], and the accuracy was, in general, not as high as he desired. On the other hand, performing a more accurate new transfer measurement was a project that no one was willing to fund at that time. He therefore agreed with his German counterparts to disagree until such time that this new measurement could be completed.

An accurate renewed comparison of the direct ac method and the transfer-to-dc measurement has now been completed and is described in Section 4. The new measurements show that a tranfer-to-dc measurement agrees with a direct ac measurement. The experimental error of our measurements is about ±1%. We therefore conclude that some error was made in the original German measurements in the 1950s and carried forward to this day.

It is comforting to know that this "mystery" has been solved. Whether the "correct" flux will ever be incorporated into the German calibration tapes is another matter. The practical fact is that, for nearly all users of calibration tapes, *consistency* is much more important than *accuracy*. Thus we expect that the actual fluxivity of calibration tapes based on the old German measurement will continue to be 10% les than the stated value, which is to say that tapes based on the old German measurement, and designated as 320 nWb/m, will continue to actually be 288 nWb/m.

1 REVIEW OF THE DIRECT AC METHOD OF FLUX MEASUREMENT

Wallace [7] described the theory of measuring tape flux directly, either in free space (a magnetic "open" circuit) or against a high-permeability head (a magnetic "short" circuit). He calculated that the open-circuit flux on *one* side of the tape is exactly half of the short-circuit flux, so long as the permeability of the head is large, as it is in practice, and the wavelength is very long, as it is at low frequencies. He also mentioned that the sensitivity factor of a head can be calculated, and that this factor "depends on the reluctances of the gaps and of the magnetic parts of the reproducing head." Finally Wallace stated that this sensitivity factor "could be interpreted as reducing the effective number of turns of the reproducing head to a value somewhat lower than the actual number of turns."

Schiesser and Schmidbauer [8] also realized that the tape flux is most easily measured with an ordinary ring-core reproducing head whose sensitivity has been calibrated, and they sought a means for calibrating the sensitivity factor of a head. They reported on work done by Hasselbach [9], who measured the open-circuit flux in a direct measurement using a single-turn nonferromagnetic reproducing head. Several other researchers also attempted to use this method (see Appendix 1) but eventually abandoned it because of the difficulty of fabricating and calibrating the head, and because wear causes a change in the calibration. Schmidbauer [1] concluded, however, that "since the normal operating condition of the tape is doubtless that of contact with a high-permeability reproducing head, the short-circuit flux should be taken as the appropriate quantity."

Westmijze [10], in part V, section 1, "Experimental Arrangement," of his classic studies, measured recorded tape flux directly by measuring the output voltage from a reproducing head having a known number of turns. He stated that "the cross-section of the . . . [magnetic] circuit is such that its reluctance is negligible compared with that of the gap." Thus his "effective" number of turns would equal the actual number of turns. Unfortunately he gives no further details of the head construction, so we are unable to evaluate his statement. Considering the thoroughness of Westmijze's work, we would certainly give him the benefit of the doubt.

Westmijze's method of direct measurement of the absolute flux fell into disuse until further work was done to determine directly the flux sensitivity of the head by the first author [5], [11]. In the latter work two types of calibrated heads were constructed and studied—a "symmetrical" head with approximately 50% flux efficiency, and a "high-efficiency" head with approximately 98% efficiency. The symmetrical head is mainly a research tool, since its use requires averaging two flux measurements, one with the front gap and one with the rear gap. The high-efficiency flux-measuring head is the basis for an AES/ANSI standard method of flux measurement [12]. A tape flux measurement by this method is comparatively simple, as it requires only a tape transport, the high-efficiency head and its calibration factors, a voltmeter, and a frequency meter.

When this method was devised in the late 1960s, ten of the high-efficiency heads were made by Ampex Corporation, and five were distributed to various interested organizations. The intention was that Ampex would manufacture and sell these heads, but they decided otherwise. For a number of years the first author was unable to find a manufacturer for these special heads—they rely on an "old-fashioned" fabrication technique that no one was using any longer. Recently we have found a manufacturer who is willing and able to make heads the "old way" with superior new magnetic materials. Thus now the high-efficiency measuring heads are commercially available.

2 REVIEW OF THE TRANSFER-TO-DC METHOD OF FLUX MEASUREMENT

Schiesser and Schmidbauer [8] also reported Hasselbach's measurement [9] of the open-circuit flux by a transfer measurement in which a second recording is made. This second recording is of a unidirectional (dc) magnetization. It is made with a dc recording current equal to the rms value of the ac recording current that produces the same flux as the unknown flux in the first (ac-magnetized) tape. Then he used a magnetometer or a fluxmeter to measure the unidirectional flux.

"Magnetometer" usually designates an instrument in which a bar magnet to be measured is placed in a small, known field. This field produces a mechanical torque on the magnet, and the induction of the magnet can be calculated from the values of the known field and the measured torque (see [13, pp. 357–362]. Modern magnetometers are described in Mee and Daniel [14], chap. 6, sec. 6.1.4).

"Fluxmeter" usually designates an instrument in which a bar magnet to be measured is inserted into (or withdrawn from) a coil, commonly called a "search coil." This motion produces a changing flux, which generates a voltage impulse across the coil terminals. This voltage is integrated and is a measure of the flux from the magnet. The integration was originally performed by a "ballistic galvanometer," which is a purely electromechanical device (that is, it has no electronics) and of comparatively low sensitivity (see [13, pp. 362–383]). More recently electronic integrators having higher sensitivity have been used, for instance, by Schmidbauer [1].

Using a correction factor for the wavelength response between direct current and the recorded ac signal, Schmidbauer calculated the value of the original unknown ac flux. This recorded flux, whose value was thus measured by a tranfer open-circuit method, could then be used to calibrate the effective number of turns of any ordinary head, which could then in turn be used for a direct flux measurement. This work is further detailed in several papers by Schmidbauer [1], [15], [16].

Link [17] used a modified single-turn nonferromagnetic head in still another transfer method for measuring the open-circuit flux. He used a 10 000-turn coil for the head. This head had a gap length of 10 mm. He recorded the very low frequency of 0.1 Hz at 95 through 760 mm/s, which resulted in a very long wavelength (from 1 to 8 m). Thus gap loss and spacing losses are negligible, even with this giant gap length of 10 mm. Link stated that this method gives measured flux values consistent with the previous German measurements using the various other open-circuit transfer flux-measuring methods described.

3 REVIEW OF THE DISCREPANCY IN FLUX MEASUREMENTS

We compared the fluxivities of the reference fluxivity sections of German (AGFA and BASF) reproducer calibration test tapes that were calibrated against the 1950s transfer-to-dc measurement; and of American (originally Ampex and later MRL) calibration tapes that were calibrated by the direct ac measurement. After taking into account the stated value of the flux,[2] we find that flux on the American tapes is consistently 10% greater than the flux on the German tapes. This corresponds to a level difference of 0.8 dB. For example, the level difference between a 320-nWb/m recording and a 250-nWb/m recording should be 20 log (320/250), which is just 2 dB. Users have reported to us that the level difference between a German 320-nWb/m recording and a U.S. 250-nWb/m recording is only 1.2 dB. This is again the 0.8-dB level difference.

We have received from the Institut für Rundfunktechnik a sample of a 1000-Hz recording at 380 mm/s (a wavelength of 0.38 mm). This recording was calibrated by Link's open-circuit flux measurement at a very long wavelength with the 10 000-turn coil. According to their measurement, the fluxivity is 320 nWb/m; according to our measurement by the ANSI direct ac method, the fluxivity is 287 nWb/m—again the 10% difference.

To put it another (and we think clearer) way: given exactly the same recorded flux, the German measurement using the transfer-to-dc method gave a value of 320 nWb/m, whereas our measurement using the direct ac method gave a value of 287 nWb/m. Therefore the sensitivity of the German flux-measuring procedure must have been 10% greater than the sensitivity of our flux-measuring procedure.

This difference was first discovered in the late 1960s, and the first author has been searching for an explanation ever since.

The first suggestion [18] was that there might be a mistake in the fundamental assumptions about the magnetics. The first calibration tape standards published (German standard DIN 45 513, pts. 1 through 4, 1955) specified the "Kurzschlußfluß"—flux in a magnetic short circuit (that is, against a high-permeability reproducing head)—and this quantity is still specified in the current versions of this standard (dated variously 1962 through 1972). Current ANSI standards [12] and IEC standards [3], [19] also specify short-circuit flux. On the other hand, the DIN tape flux *measurement* standard [4] describes only transfer-to-dc methods and measurement of the *open-circuit* flux (the flux in free space), because these were the only techniques developed at that time. The 1973 version of that standard added Link's method, but this is still a transfer measurement of the open-circuit flux. So we inquired into the possible effects of open- versus short-circuit conditions—could

[2] And for the Ampex tapes, which used 700 Hz as the reference frequency, taking into account the reference frequency and the standard equalizations.

this cause the open-circuit (German) measurement procedure to be 10% more sensitive than the short-circuit procedure?

3.1 Vertical Component as a Source of Error

Schmidbauer discusses the longitudinal and vertical components of flux in [1, sec. 5]. He explains that the fluxmeter method of measuring the open-circuit flux measures only the longitudinal flux, whereas the short-circuit method measures the total flux (magnitude of the sum of the longitudinal and vertical components). He describes experiments that show that the vertical component is negligible except when the recording is overbiased. So the vertical component should not be the cause of any discrepancy. Furthermore, if the vertical component were significant, this would cause the short-circuit measurement to be *more*, not less, sensitive. This eliminates the vertical component as a cause of the difference.

3.2 Demagnetizing Field as a Source of Error

Second, the short-circuit condition would remove any demagnetizing field that might exist in the open-circuit condition. But this would also cause the short-circuit flux measurement method to be *more*, not less, sensitive than the open-circuit method. This eliminates the demagnetizing field as a cause of the difference.

3.3 Head Not Being a Short Circuit as a Source of Error

Third was a suggestion that the flux-measuring head used in the short-circuit measurement was not really a short circuit, and that the reluctance of the path around the head was not very small compared to that of the path through the tape. A calculation shows that the ratio of reluctances is in fact 10^5 for the high-efficiency head and 3×10^3 for the symmetrical head. Both of those ratios would eliminate this effect as a source of error.

3.4 Conclusion

There is nothing in the fundamental magnetics that predicts that the sensitivity of the open-circuit measurement procedure should be greater than that of the short-circuit measurement procedure. So we must look elsewhere.

4 NEW MEASUREMENTS

Although Schmidbauer's work [1] seems to be accurate and comprehensive, we have no direct access to his equipment, nor to the complete details of his measurements, nor to the physical quantities—that is, to his ac and transfer-to-dc recordings. Therefore we have repeated the measurements, directly comparing the two (direct ac and transfer-to-dc) methods. Increased accuracy of measurements is now possible due to many advances made in measuring instruments, electronics, tape recording and reproducing theory, and tape in the years since the original work. For instance, an inexpensive digital multimeter (Fluke 8050A) gives an accuracy better than ±1.0% for measurements of resistance and of ac and dc voltage and current in the ranges we use. The analog meters we used in the 1960s typically had an accuracy of ±3%. We will describe here the more interesting details of the other equipment and procedures that have given us improved accuracy. Concerned engineers can obtain a copy of the detailed report of measurements, sources of error, and samples of the ac- and dc-magnetized tape, if they wish to verify these measurements themselves.

Many different track widths are used in practical studio recording. But for an accurate measurement, the recorded track width must exactly equal the reproduced track width, and their locations must be exactly coincident. The only really satisfactory solution that we know of for an accurate measurement is to use a full-track system and to have all heads *wider* than the tape. Therefore all measurements were done with a full-track (nominally 6.3-mm-wide) recording.

The tape speed for all measurements was 380 mm/s (15 in/s), and the frequency, if alternating current, was 1000 Hz unless otherwise specifically stated. All ac values of voltage, current, tape flux, and so on, are rms values.

4.1 Blank Tape

Schmidbauer noted that "a blank tape with the least possible sensitivity variations should be used . . ." [1]. Some modern mastering tapes have very uniform sensitivity (about ±0.1 dB) at long and medium wavelengths. This is probably much better than Schmidbauer had available to him, but his papers do not give details on the sensitivity variations for the tapes he used.

All of our ac and dc signals were recorded on one 760-m roll of Ampex 456 tape. The manufacturer's specification is coating thickness 14 μm and remanence fluxivity 1460 nWb/m. The reversible relative permeability[3] in the head-to-medium motion direction μ_x is 1.68, and that in the direction vertical to the medium plane μ_y is 3.12. The tape width, measured with a micrometer table on a microscope, is 6.27 mm.

This roll of tape was tested for uniformity of 1000-Hz sensitivity for its full length.[4] The sensitivity level varied by less than ±0.1 dB.

4.2 Recording System

The recording system consists of a Studer A80 transport, with a Studer head base on which are mounted one each full-track (7-mm-wide-core) erasing head, re-

[3] The permeability data were supplied in 1976 by H. Neal Bertram, then of Ampex Corp.

[4] When previously testing uniformity of tape sensitivity using a stock Studer reproducing head, we have found that the sensitivity level of the system increases about 0.1 dB from the beginning to the end of the tape. Interestingly, this was observed for many rolls of tape. More interestingly, the same effect was observed *when starting from either end of the tape*. So obviously we were *not* measuring a change in the tape sensitivity, but something else. Measurement of the recording head signal current and bias current showed that these were constant. By elimination, we eventually discovered that the effect occurred only when recording and reproducing simultaneously. The cause was that the erasing head gets rather warm,

cording head, and high-efficiency reproducing head. The erasing head is essentially a stock Studer A80 head operated with 90 mA of 80-kHz erasing current, which erases a 1000-Hz signal level by 84 dB. The recording head is a Saki ferrite head with a 7-μm gap length and a two-turn winding. (The inductance is about 1 μH.) The recording head constant-current driver is custom built (see Fig. 1), with two dc-coupled operational amplifiers and a dc offset-null control. The 240-kHz bias (from the Studer A80) is controlled by a 10-turn potentiometer with a mechanical digital turns counter. The signal is controlled by another 10-turn pot with a digital turns counter. The two signals are mixed into the virtual-ground input of the TL 071 operational amplifier. This output feeds an LH 0101 operational amplifier connected in a voltage-to-current configuration with a head-current-sensing resistor. The 10-turn pots with digital turns counters provide repeatable gain settings. Mixing into a virtual ground provides isolation between the signal and the bias gains.

The dc coupling allows recording ac or dc signals by simply changing the input voltage to the recording amplifier. The dc offset of the recording current from all of the system elements was set to zero using the dc-offset-null control.

This recording system is much more stable and more flexible than that used previously by the first author [5].

and enough of this heat is transferred by the tape to the reproducing head to warm it appreciably. When the reproducing head laminations warm, their permeability increases. We measured this independently by measuring the inductance of a toroid of the head core material placed in an oven. This increase in core permeability causes the efficiency of an ordinary head to increase, producing the false appearance that the tape sensitivity increases as you go through the roll of tape. This effect does not occur with the high-efficiency reproducing head, because such a small part of the total head reluctance is contained in the core that the change in reluctance does not sensibly change its efficiency. Thus this head does not show the erroneous "rising tape sensitivity" effect.

4.3 AC Reproducing System

The ac reproducing system is based on a high-efficiency flux-measuring head. The general principles of the head construction and calibration are described in [5]. The head used here, marked "2," was manufactured for us by Flux Magnetics of Oakley, CA. It has 1000 turns, a mechanical gap length of 12.80 μm, a gap depth of 381 μm, and 150-μm laminations of Hy-Mu 800, with a permeability at 60 Hz of 35 000. The head inductance at 1000 Hz is 280 mH. The flux efficiency was 97.2%, measured by comparing its generated emf to the average emf from the two gaps of the symmetrical head no. 395 of [5], taking into account the number of turns (2000), the gap loss, and the efficiency (49.5%) of the symmetrical head.

In the previous paper [5], and in the AES/ANSI standard [12], we measured the head output voltage directly. Although this is simple in principle, it causes several practical problems, which we will discuss. In this new work we avoid these problems by mounting a simple integrating operational amplifier on the head assembly, "just like a real tape reproducer." The reproducing head integrating amplifier schematic is shown in Fig. 2. Its advantages are as follows:

1) Like all Faraday's law heads, the electrical signal produced by this head is proportional to the derivative (rate of change) of the tape flux. Therefore when the head voltage is measured directly, it is also necessary to measure the exact signal frequency. But when the signal is integrated, the frequency becomes one of the calibration factors of the integrator, and no longer needs to be a part of the flux measurement: the system output voltage becomes directly a measure of the tape flux.

2) Without the amplifier, the head-to-voltmeter and -frequency meter interconnection is subject to noise and hum pickup. With the integrating amplifier, the interconnecting leads are short, and the frequency meter connection is eliminated. The built-in amplifier then increases

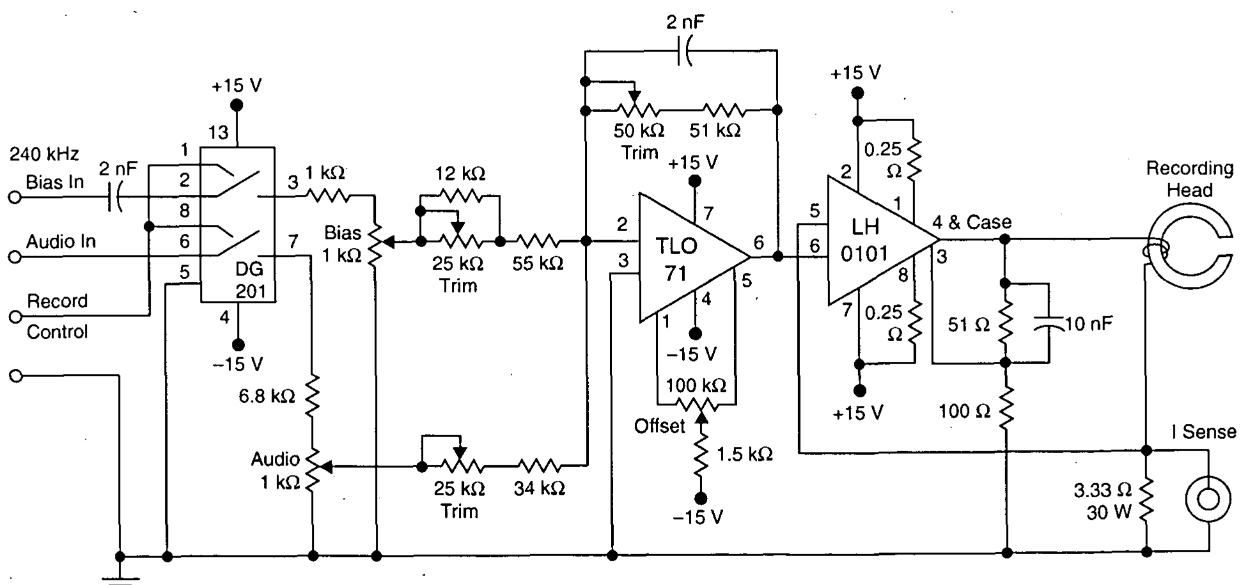

Fig. 1. Recording amplifier schematic.

the head voltage and reduces the circuit impedance, thereby eliminating the noise pickup problem.

3) Most voltmeters have reduced accuracy for low (millivolt-range) voltages, and most frequency meters require more input voltage than the head delivers. The built-in amplifier raises the voltage into the most accurate range of the voltmeter. The frequency meter has been completely eliminated from the flux measurement.

4) The load impedance on the head affects its frequency response. But this load will, in general, be unknown, because it depends on the cable type and length, and the input impedance of the voltmeter and any other auxiliary equipment connected (such as a frequency meter and an oscilloscope). With an amplifier included, the load impedance on the head can be a known and fixed value, and that value can be designed to resonate the head with the Q required to compensate for the gap-length loss at any chosen single speed, as described in [20]. We compensated the gap loss so that the flux response at 380-mm/s tape speed is ±0.1 dB up to 14 kHz.

5) Conversion from head voltage to tape fluxivity requires a calculation with several factors:

$$\frac{\Phi}{w} = \frac{e_h}{2\pi f w N \eta}$$

where Φ/w is the flux per unit track width (fluxivity) in webers per meter, e_h is the head emf in volts, f is the frequency in hertz, w is the track width in meters, N is the number of turns wound on the head, and η is the flux efficiency of the head. With a built-in integrating amplifier, all of the calibration factors can be included in determining the integrator gain, and the integrator gain can be scaled so that the fluxivity-to-voltage ratio is a convenient value. To make the system sensitivity so that 1-V output corresponds to a fluxivity of 100 nWb/m, with a track width of 6.27 mm (the measured tape width), 1000-turn winding, and a head efficiency of 0.98, we set the integrating amplifier voltage gain at 1000 Hz to

$$G = \frac{e_o}{e_i} = \frac{1\ \text{V}}{2\pi \cdot 1000 \cdot 100\ \text{nWb/m} \cdot 6.27\ \text{mm} \cdot 1000\ \text{Hz} \cdot 0.98} = 259 .$$

The long-wavelength response of any reproducer is limited by the long-wavelength response of the head, as Schmidbauer noted: ". . . at long wavelengths, the wavelength is comparable to the reproducing head dimensions (the head face length, the length of the contact between the tape and the head face, and the size of the head shields). At these wavelengths the reproducing head has an appreciable wavelength response, and that response must be taken into account." [1]. Since Schmidbauer's work, more explanations of the theory of long-wavelength reproduction have been published [21]. Probably more importantly, we are aware that the long-wavelength response due to the "secondary gap effect" [22] can be eliminated by using a very high-efficiency head.[5]

Still, it is difficult to calculate accurately the long-wavelength response of a head. Fortunately it is simple enough to measure by using a tape with a very thin coating. The recording response of any tape is flat from direct current up to some wavelength where the respone begins to fall off. We used Ampex 705 logging tape, which has a coating thickness of 4.3 μm. The combination of the recording and reproducing systems' responses, including the Ampex 705 tape, measured ±0.05 dB from 140 to 1100 Hz (wavelengths of 2.7 to 0.35 mm). Since the response of the recording electronics and the wavelength response of the tape are flat over this bandwidth, the response of the reproducing system is flat within this limit over this bandwidth. Below 140 Hz the head response undulates up to a maximum of +2.7 dB at 25 Hz, then falls off.

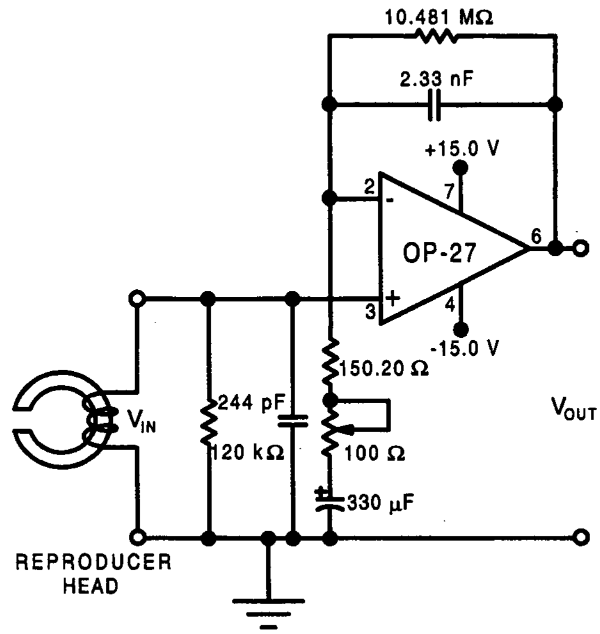

Fig. 2. Reproducer head integrating amplifier.

4.4 Recordings

Using the roll of blank tape described in Section 4.1, with a 1-kHz signal, the bias current was set for maxi-

[5] There is a tradeoff in choosing the gap length for a high-efficiency flux-measuring head. As the gap length becomes longer, the short-wavelength loss becomes significant, but the head's efficiency increases to nearly 100%, and it will therefore have a negligible "secondary-gap" long-wavelength response. A further advantage of a nearly 100% efficiency head is that the flux sensitivity does not increase with head wear. The gap-loss function is now well known, and it is easily compensated very accurately. On the other hand, it is difficult (if not impossible) to calculate the secondary-gap response accurately. Therefore it seems desirable to use a long enough gap to achieve about 98% efficiency, and compensate the short-wavelength loss as required.

mum recording sensitivity (the geometric mean of the bias pot readings for 0.1-dB reduction in sensitivity for overbias and underbias). Then, using the ac reproducing system described, the recording gain control was set so that an ac input voltage of 1 V to the recorder would produce an ac output voltage of 3.55 V from the reproducer, corresponding to a flux of 355 nWb/m according to the direct ac measurement. A length of tape was recorded. Then the ac input of 1 V was replaced by a dc input of 1 V and a length of tape recorded. Finally the polarity of the direct current was reversed, and another length of tape was recorded.

4.5 DC Measuring System

In the first author's previous work [5] he used a vibrating sample magnetometer (VSM), but it turned out to be less convenient and less accurate than he had hoped. Therefore our dc flux-measuring system is now identical in principle to that used by Schmidbauer [1]—the output voltage of a search coil with a known number of turns is integrated with an integrator having a known sensitivity, and the output voltage of the integrator gives a measure of the tape flux.

We copied Schmidbauer's search coil, shown in his fig. 5. The similarity of the mechanical constructions is shown by the fact that he measured the mutual inductance between this two coils as 108 mH. We measured the mutual inductance between our two coils as 109.4 mH, a difference of only 1.3%.

Schmidbauer's integrator [1] used vacuum tubes, which do not have good dc stability. Therefore he used an ac-coupled integrator, followed by a peak-holding circuit, and a d'Arsonval (analog electromechanical) milliammeter. He calibrated his system with several values of current impulses.

We, on the other hand, took advantage of a modern chopper-stabilized operational amplifier, the Linear Technology LTC1050, and built an operational-amplifier integrator, as shown in Fig. 3. We measured its output voltage

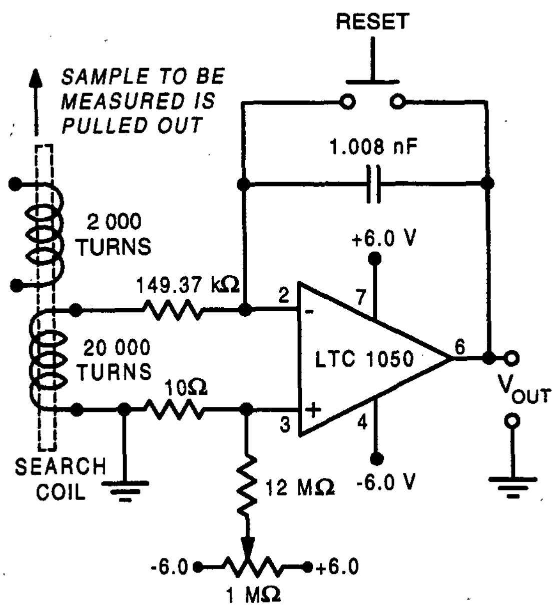

Fig. 3. Integrating amplifier for search-coil fluxmeter.

with a Fluke 8050A digital multimeter. This integrator is more simple, stable, and sensitive than that used by Schmidbauer. It integrates over the range of 1 mHz to 1 kHz, and this allows us to use several methods to measure and confirm the sensitivity of the flux-measuring system, as detailed in Appendix 2. The flux sensitivity (ratio of input flux to output voltage) is 7.889 nWb/V.

4.6 Determining the Wavelength Loss in the Recording and Reproducing Process

In making a transfer-to-dc measurement, there is a short-wavelength flux loss inherent in the recording and reproducing process, the so-called thickness loss. The DIN measurement standard [4] requires, and the Schmidbauer background paper [1] discusses, making this correction for the thickness loss.

4.6.1 Wavelength Response Theory

The calculation of the recording wavelength loss has had a long history. Here is a summary:

1) All early researchers made the reasonable (but, it eventually turned out, incorrect) assumption that the recorded magnetization is constant through the depth of the tape, and that the medium is isotropic (that is, the permeability is the same in all directions):

a) Wallace calculated the wavelength response for a tape with a relative permeability of 1 [7].
b) Westmijze calculated the wavelength response for tape with any value of relative permeability [10].

Schmidbauer [1] used Westmijze's formula, with a permeability of 2.5 and a coating thickness of 12 μm, for his recording of 1000 Hz at a tape speed of 380 mm/s to arrive at a 5% (0.42-dB) correction. He realized that this formula was only an approximation and commented that "one must then count on a measurement uncertainty of this order of magnitude." He assumed that, at this wavelength, there was no spacing loss due to the tape surface roughness.

These theories, which assume constant magnetization with depth—however "reasonable"—are clearly in error. They predict that the recorded flux from a constant magnetizing field falls asymptotically to 6 dB per octave at short wavelengths, whereas a measured wavelength response actually falls asymptotically to 12 dB per octave.

More recently a better theory for the recording and reproducing loss has been published:

2) Assuming that the recorded magnetization is proportional to the distance from the tape surface to the coating:

a) Bertram calculated the wavelength response for an isotropic medium (tape) with a relative permeability of 1 [23].
b) Bertram then also calculated the wavelength response for an ac recording, biased for maximum sensitivity at long wavelength (as we have done here), using an anisotropic medium with any values of longitudinal and vertical relative permeabilities of the tape [24].

In this last case we need to know not only the coating thickness but also the longitudinal and vertical permeabilities of the tape, which are very much affected by the tape orientation. These permeabilities are not published by the tape manufacturers, and are not easily measured in the ordinary electronics laboratory.

Fortunately Bertram has supplied us with the permeability values of the Ampex 456 tape, which we are using (see Section 4.1). Using these values and Bertram's eq. (22), the calculated loss between 0 and 1000 Hz, at 380 mm/s, is 0.5 dB.

4.6.2 Wavelength Response Measurement

As Schmidbauer concluded [1, sec. 6 in the translation], the theoretically calculated recording loss should also be measured by reproducing the recording. Using the tape described in Section 4.1, and the recording and reproducing system described in Sections 4.2 and 4.3, the wavelength loss between 140 and 1000 Hz, at 380 mm/s, measures 0.36 dB. The loss from direct current to 140 Hz, calculated from Bertram's eq. (22), is 0.06 dB. Therefore the total wavelength loss between direct current and 1000 Hz is 0.06 + 0.36 dB = 0.42 dB. Thus the calculated and measured losses between these frequencies differ by only 0.08 dB, or 0.9%.

We chose to use the calculated wavelength loss between 0 and 1000 Hz, which is 0.5 dB (corresponding to a ratio of 0.9441).

4.7 DC Flux Measurements

The dc recordings were cut into 300-mm lengths (as Schmidbauer had done) and stacked into bundles of 14 pieces. By making a rectangular cut at one end and a diagonal cut at the other end, we were assured that no piece of tape was accidentally inverted in the stack.

The fluxmeter output voltage was 3.815 V for one recording polarity and 4.529 V for the other, for an average of 4.172 V, corresponding to a total flux of 32.913 nWb, or 2.351 nWb for a single layer of tape, at direct current.

The direct current in the recording head had been set to 0 mA for an input of 0 V, which produces this flux asymmetry of ±9%, corresponding to a dc flux level re 355 nWb/m of −21 dB. Although this would have produced an appreciable error in the flux measurement if it were not averaged out, it was not enough of an error that we attempted to eliminate it by readjusting the dc-balance control.

Finally we corrected the flux for the wavelength loss between direct current and 1000 Hz, the factor 0.9441 from Section 4.6.2, and converted total flux to fluxivity using the measured tape width of 6.27 mm to arrive at a fluxivity of 354 Wb/m, according to the transfer-to-dc method.

5 CONCLUSION

We made tape flux measurements by the direct ac method of AES 7 (ANSI S4.6) [12] and by the transfer-to-dc method of German standard DIN 45 520 [4], and we found that the two methods give the same results. The experimental error of our measurement is about ±1%.

The original German measurements made in the 1950s, using the transfer-to-dc method, reported a 10% greater flux than our new measurements. We conclude that these original measurements must have been in error.

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APPENDIX 1 SINGLE-TURN NONFERROMAGNETIC REPRODUCING HEADS

In the beginning, the single-turn nonferromagnetic reproducing head appeared to be the best way to measure tape flux because it avoided the problem of having to determine the efficiency of a ferromagnetic head. Reports on such work were published by Daniel and Axon [25], Schmidbauer [15], and Schwartz, Wilpon, and Comerci [26].

Eventually they concluded that there were insurmountable problems with these heads. They require special construction techniques and are very difficult to make with sufficient accuracy, whereas the ferromagnetic heads are similar to standard production heads. Worse, if the "single turn" is a round wire, it must have a very small diameter and is difficult to place in a straight line. The tape will wear it through rather quickly.

An alternate construction was to deposit the "single turn" on a plate of glass. But the wavelength response of this head depends on the depth of the "turn." It proved impossible to measure this depth with sufficient accuracy, and the wavelength response had to be measured experimentally, which was also subject to errors that were unacceptably large.

This method was eventually abandoned.

APPENDIX 2 DC FLUXMETER DESIGN AND CALIBRATION

A2.0 Introduction

The dc fluxmeter used here consists of a search coil and an integrating amplifier. The search coil is essentially identical to the coil used by Schmidbauer [1]. The integrating amplifier is of our own construction, using a chopper-stabilized operational amplifier. The search coil form also carries an auxiliary coil used as a mutual inductance for calibrating the sensitivity of the fluxmeter; this also copies Schmidbauer.

We calibrate the fluxmeter sensitivity by several different methods. First we determine the integrator gain by measuring the integrating resistance and capacitance components and also by measuring its ac gain. From this we calculate a flux-to-voltage sensitivity. Second (the method used by Schmidbauer), we determine the mutual inductance between the auxiliary coil and the search coil (by two different methods), use the relationship between input current and mutual inductance to generate a known input flux, and use this input flux to measure a flux-to-voltage sensitivity. All of these measurements were consistent within better than 1%.

A high-sensitivity fluxmeter is easy enough to construct. The limitation on *usable* sensitivity is set by the drift of the fluxmeter. The drift is further discussed in the next section. The sensitivity required of the fluxmeter can be reduced by stacking more layers of recorded tape, which increases the flux to be measured. One piece of tape, 6.27 mm wide, recorded with a fluxivity of 355 nWb/m, produces a flux of 2.226 nWb. Schmidbauer used 30 to 50 pieces of tape, so he had a total flux of around 60 to 100 nWb. We used 14 strips at 355 nWb/m each (as well as 10 strips at 500 nWb/m each) for a total flux of approximately 31 nWb.

A.2 Search Coil and Auxiliary Coil

A2.1.1 Principles of Flux Measurement

From Faraday's law of induction, the instantaneous emf e generated in a coil of n turns from a rate of change of flux $\mathrm{d}\Phi/\mathrm{d}t$ is

$$e = n\frac{\mathrm{d}\Phi}{\mathrm{d}t}\,. \tag{1}$$

For a sinusoidal signal of frequency f, this may be rewritten as

$$E = n \cdot 2\pi f \Phi\,. \tag{2}$$

A2.1.2 Description

The search coil assembly is shown in Fig. 4 (from Schmidbauer). The search coil has n = 20 000 turns. The measured inductance is approximately 4 H, and the resistance is 6826 Ω. Because the coil's resistance and inductance are in series with the integrator input resistance R_i, they may not be neglected in calculating or measuring the gain of the integrator.

The auxiliary coil has 2000 turns. The measured inductance is approximately 66 mH, and the resistance is 387 Ω.

A2.1.3 Calibration by Mutual Inductance Measurement

The mutual inductance M between the search coil and the auxiliary coil can be calculated from the measured inductance for a series aiding connection (L^+ = 4.305 H) and for a series opposing connection (L^- = 3.867 H); then $M = (L^+ - L^-)/4$ = 109.5 mH. This value agrees quite well with Schmidbauer's measurement of 108 mH.

Sources of error: The inductances were measured at 1000 Hz with a Hewlett-Packard model 4192A low-frequency impedance analyzer, whose error is ±0.27% for the individual measurements. It is hard to know what error is in the mutual inductance, because in this case M is the small difference (about 10%) between two large numbers (L^+ and L^-). If both measurements are in error by the same amount, then the error in M would be the same as the instrument error. But if one error were +0.27% and the other error were −0.27%, then the error in M would be 0.54% of L, which is 5% of M.

For an alternate measurement of mutual inductance we have another useful relationship [27]: the secondary emf e of a transformer is the mutual inductance M times the rate of change of the primary current $\mathrm{d}i/\mathrm{d}t$,

$$e = M\frac{\mathrm{d}i}{\mathrm{d}t} \tag{3}$$

which, for a sinusoidal signal of frequency f, may be rewritten as

$$E = M \cdot 2\pi f I\,.$$

Measuring at 99.9 Hz, I = 9.026 mA, E = 619 mV, and M = 109.3 mH, which agrees with the series aiding and series opposing method (difference = 0.2%).

We will use the average of the two measurements, M = 109.4 mH.

A2.2 Integrator

Our integrator consists of a chopper-stabilized operational amplifier (Linear Technology LTC 1050) with an input resistor R_i and a feedback capacitor C_f. The integrator is characterized by its time constant $\tau = R_\mathrm{i}C_\mathrm{f}$. (This is sometimes called the integrator gain, but it must not be confused with the ac gain, which is a function of frequency.)

In general the instantaneous integrator output voltage u_o equals the time integral of the input voltage $\int^t u_\mathrm{i}$ divided by τ,

$$u_\mathrm{o} = \int^t \frac{u_\mathrm{i}}{\tau} \tag{4}$$

which, for a sinusoidal signal of frequency f, may be rewritten as

$$U_\mathrm{o} = \frac{U_\mathrm{i}}{2\pi f \tau}\,. \tag{5}$$

Sources of error: The integrator circuit has a small drift rate which can be compensated with an offset con-

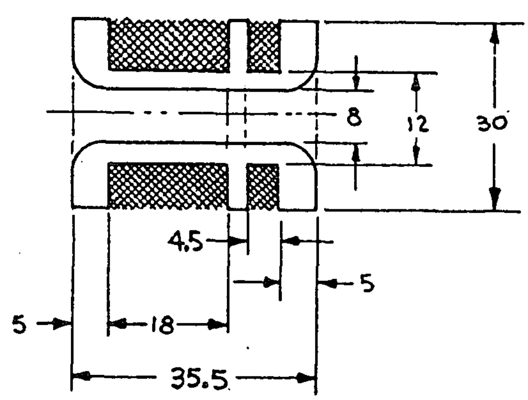


Fig. 4. Bobbin for fluxmeter search coil with a mutual inductor for calibration. All dimensions in millimeters.

trol. In addition there is some random drift which causes an error in the output reading. If we zero the integrator and allow, say, 3 s for withdrawing the tape and reading the voltmeter, the drift is about 1 mV. The relative error of course depends on the actual voltage read. Typically it is around 1 V, so a typical error would be 0.1%.

Because the system is very sensitive, very small thermal and magnetic changes cause the output voltage to "drift." We mounted the integrating amplifier in an enclosed metal box to reduce thermal drift. Magnetic drifts come from several sources. Moving any magnetic object within about 2 m of the pickup coil produces a detectable output voltage. This includes small tools and a steel chair. Further, any motion of the search coil, which is in the earth's field, produces a detectable output voltage. Proper orientation of the search coil minimizes its sensitivity to motion.

A2.2.1 Integrator Gain Calibration by Static R and C Measurement

One means of calibrating the integrator gain is to make a static measurement of the values of input resistance R_i and feedback capacitance C_f, and simply calculate

$$\tau = R_i C_f \; . \tag{6}$$

The measurement accuracy obviously depends on the accuracy of the resistance and capacitance measurements.

We have used nominal values R_i = 150 kΩ and C_f = 1 nF. Measured values are R_i = 149 370 Ω and C_f = 1.008 nF.

Sources of error: Resistance measured with a Fluke 8050A digital multimeter: Error on the 200-kΩ range, ±(0.05% of reading + 2 digits), with 10-Ω resolution, which totals 0.05% + 0.01%, or ±0.06%.

Capacitance measured with a B&K Precision 830 capacitance meter. Error ±(0.2% of reading + 1 digit + 0.5 pF), with 1-pF resolution, which totals 0.2% + 0.15%, or ±0.35%.

Thus for the integrating amplifier only τ = 150.565 μs, with an error of the root-sum-square (RSS) of 0.06% and 0.35% = ±0.35%.

In actual use, of course, the search coil's impedance is in series with the coil's voltage and the integrator's input resistor R_i. So we recalculate and remeasure to take that into account.

The coil resistance of 6 826 Ω is 4.5% of R_i, so that cannot be neglected. The total input resistance R_{ti} becomes 156 196 Ω.

We estimate that the tape is withdrawn from the coil in about 200 ms, so the spectrum of the emf in the coil when the tape is withdrawn would have a fundamental frequency of about 5 Hz and negligible harmonics by 100 Hz. At 100 Hz the 4-H inductance has an impedance of 2500 Ω. This would change the voltage division due to the source impedance (the RSS of the coil resistance and the coil inductive impedance) by 0.2%, so the effect of the inductance should negligible. Thus for C_f = 1.008 nF and R_{ti} = 156 196 Ω, τ = 157.4456 μs.

A2.2.2 Integrator Gain Calibration by AC Gain at Frequency Measurement

For the case where the input signal is a sinusoid, the integrator has a voltage gain at a specific frequency f, given by Eq. (5), which can be manipulated to

$$\tau = \frac{U_i}{2\pi f U_0} \, . \tag{7}$$

Thus one can also calibrate the integrator by measuring the integrator's voltage gain at some frequency and calculating τ.

Again using the system of coil and integrator, with a test frequency of 99.9 Hz, we measure U_i = 106.08 mV and U_o = 1068.8 mV. Thus τ = 158.127 μs.

Sources of error: The measurement error depends on the accuracy of the voltage ratio measurement (absolute accuracy of the voltage is irrelevant) and the frequency.

Voltage measured with a Fluke 8050A digital multimeter: 100 mV on a 200-mV range; 1000 mV on a 2000-mV range. Error ±(0.5% of reading + 10 digits), with 100-μV (or 1-mV) resolution, which totals 0.5% + 0.1%, or ±0.6%.

Frequency measured with Heathkit IM 4100 frequency counter: Error <0.01%.

Thus τ = 158.127 μs with an error of the RSS of 0.01% and 0.6% = ±0.6%.

A2.2.3 Comparison of Time Constant Measurements

Measured time constants τ (157.446 μs by *RC* measurement in Section A2.2.1, 158.127 μs by gain measurement in Section A2.2.2) differ by 0.4%; we will use the average value, τ = 157.8 μs.

A2.2.4 System Flux Sensitivity from Time Constant Measurement

Combining Eq. (1), Faraday's law, with Eq. (4), the integrator response, we get the flux sensitivity of the fluxmeter system,

$$\frac{\Phi}{U_o} = \frac{\tau}{n} = \frac{157.8 \ \mu\text{s}}{20\ 000} = 7.889 \ \text{nWb/V} \, . \tag{8}$$

A2.3 Calibration by Mutual Inductance Method

The sensitivity by the mutual inductance method (see Schmidbauer [1]) is

$$\frac{\Delta\Phi}{\Delta I} = \frac{M}{N_1}[\text{H}] = \frac{109.4 \times 10^{-3}}{20\ 000}\left[\frac{\text{Wb}}{\text{A}}\right] = 5470\left[\frac{\text{nWb}}{\text{A}}\right] . \tag{9}$$

For calibration, Schmidbauer used a step of direct current as the input and measured the dc output voltage. Because our system response goes from near direct current[6] to a few kilohertz, we can calibrate using a dc step or a sinusoidal ac voltage.

[6] The minimum voltage level gain of the LTC 1050 is 130 dB, corresponding to 3.16×10^6. The integrator gain is given by Eq. (5). Thus for $\tau \approx$ 160 μs, integration stops at about 0.3 mHz.

A2.3.1 Measurement with DC Step Input (Current Reversed)

A 3.560-mA input current through the secondary coil, when switched to −3.560 mA, produces an integrator output voltage of 4.886 V, which is a current sensitivity of

$$\frac{u_o}{i} = 686.2 \text{ V/A}. \tag{10}$$

Dividing the current sensitivity from the measured mutual inductance of the search coil, Eq. (9), by the gain sensitivity of the fluxmeter from the reversed current dc step measurement, Eq. (10), gives a measure of the flux sensitivity of the system,

$$\frac{\Phi}{U_o} = \frac{5470\,[\text{nWb/A}]}{686.2\,[\text{V/A}]} = 7.97 \text{ nWb/V}. \tag{11}$$

A2.3.2 Measurement with Sinusoidal Input at 100.1 Hz

An rms input current to the auxiliary coil of 1.98795 mA produces an rms output voltage from the fluxmeter of 1.3719 V, for a current sensitivity

$$\frac{u_o}{i} = 691.1068 \text{ V/A}. \tag{12}$$

Dividing the current sensitivity from the measured mutual inductance of the search coil, Eq. (9), by the gain sensitivity of the fluxmeter from the sinusoidal ac current measurement, Eq. (12), gives another measure of the flux sensitivity of the system,

$$\frac{\Phi}{U_o} = \frac{5470\,[\text{nWb/A}]}{691.1068\,[\text{V/A}]} = 7.9148 \text{ nWb/V}. \tag{13}$$

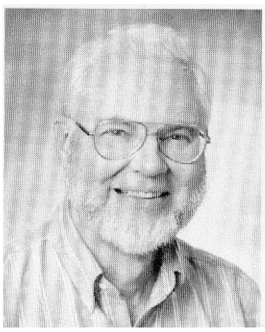
A2.3.3 Comparison of Mutual Inductance Measurements and Time Constant Measurements

The results of dc-step and ac sensitivity measurements of Eqs. (11) and (13) differ by 0.7%; their average is

$$\frac{\Phi}{U_o} = 7.94 \text{ nWb/V}$$

which is also within 0.7% of the sensitivity measurement from the integrator gain given in Eq. (8).

THE AUTHORS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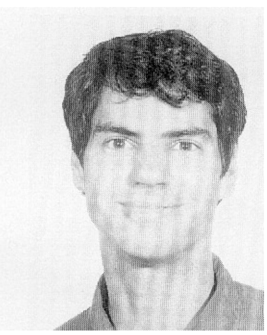
B.E. Cortez


J.A. McKnight

John G. (Jay) McKnight was born in Seattle, Washington, in 1931. He received his B.S. in electrical engineering from Stanford University in 1952, and worked at Ampex Corp from 1952 thru 1972, serving in the magnetic recording research group, the stereo tape division, and the professional audio division. At Ampex, in addition to research, he also worked on the design of the CinemaScope reproducer system; the Models 350, PR-10, and MR-70; improvements in the high-speed duplication system and operating procedures at the Ampex Music (Stereo Tape) Division; and developed the Ampex Master Equalization (AME). He has published over 60 technical papers on the theory and practice of magnetic recording and on audio engineering.

From 1972 to 1974 he was a consultant on audio systems and magnetic recording. In 1973/1974 he was a member of Judge Sirica's Advisory Panel on White House Tapes, and in 1977 to 1979 a member of the Committee on Evaluation of Sound Spectrograms of the National Academy of Sciences.

He is a cofounder of Magnetic Reference Laboratory (MRL) in Mountain View, California, where he was engineering vice-president from 1972 to 1975, and has been president since 1975. He also develops new products and directs engineering at MRL.

Mr. McKnight is a fellow and an Honorary Member of the Audio Engineering Society (AES), was president of the Society for the year 1978/1979, and received the AES Award. He is a member of the AES *Journal* Review Board, has been a governor three times, chairman of the Standards Committee, and chairman of the Publications Policy Committee. He has been a member of standards committees on audio engineering and magnetic recording of the AES, ANSI, CCIR, EIA, IEC, IEEE, NAB, RIAA, and SMPTE, and is presently a vice-chairman of the AES Standards Committee. He is also a senior member of the IEEE.

His hobbies include hiking and knapsacking; programming in the Forth computer language, and playing viola in amateur string quartets, in community orchestras, and in the orchestras of Gilbert & Sullivan companies.

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Benito E. Cortez was born in Athens, Greece, in 1965 and received a B.S.E.E. from Santa Clara University, Santa Clara, CA, in 1987. He was an engineer with Magnetic Reference Laboratory from 1987 to 1995. While assisting Jay McKnight with various aspects of this experiment, Mr. Cortez designed and implemented various components of MRL's computer-automated manufacturing system.

He is currently a sound designer and programmer specializing in sound for electronic toys with Music Annex Recording Studios in Menlo Park, CA. He designed and programmed the sounds for "Tickle Me Elmo" and "Sing 'n Snore Ernie" stuffed toys that became popular during the 1996 and 1997 holiday shopping seasons.

In his spare time, he enjoys playing classical, jazz, and folk music on the violin. Mr. Cortez is a member of the AES.

Jeffrey A. McKnight was born in San Jose, California, in 1966 and received an M.S.E.E. from the University of California, Davis, in 1992.

He worked as chief engineer at KDVS-FM from 1989 to 1991, and has been a consulting engineer for Magnetic Reference Laboratory since 1987. Currently, he is the network administrator at Music Annex Recording Studios in San Francisco and Menlo Park.

In his spare time, he is a freelance network management consultant, experimental composer, and tube amplifier enthusiast. Mr. McKnight is a member of the AES.