Low-Frequency Response Calibration of a Multitrack Magnetic Tape Recording and Reproducing System*

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Several practical problems make the use of the usual reproducer calibration test tape unsatisfactory below 1000 Hz at a tape speed of 380 mm/s. First, the low frequency equalization standards below 50 Hz are often not followed in practice. Second, there are many different multitrack formats, and this makes a true multitrack reproducer calibration tape commercially infeasible; but although one can calculate a fringing compensation, it is not accurate at the lowest frequencies. Third, the reproducer response inherently undulates, but there are not enough test frequencies to characterize that response.

At long wavelengths (low frequencies) the recorded flux is directly proportional to the recording current. Therefore system calibration is best performed by the following method: standardize the *recording* response (recording head current versus frequency); use recording and reproducing heads of the same core width throughout the system; record a slowly swept-frequency test signal; and adjust the reproducer low-frequency equalizer for flattest overall response.

1. INTRODUCTION: Calibrating the frequency response of a magnetic tape reproducer is usually a simple process: purchase a reproducer calibration test tape from one of the manufacturers of these tapes, play it, and write down the output level versus frequency, or adjust the reproducer equalizers for constant output voltage level versus frequency.

However, at medium to low frequencies—below 1000 Hz at a tape speed of 380 mm/s (15 in/s)—there are several important sources of error that make this approach inaccurate.

1) The equalization standards below 50 Hz are often not followed in practice.

2) Head core widths, and therefore track widths, are not standardized in practice, and although fringing response calculations exist, they are not accurate at the lowest frequencies.

3) There are too few frequencies on the usual calibration tapes to characterize accurately the undulating low-frequency response.

The theoretical basis for standardization has been described previously by Bertram [1] and by McKnight [2]. Some of the sources of errors have been described in another paper by McKnight [3] and also in the tape recorder manufacturers' instruction manuals. They point out that some of these errors can be avoided by using the *recording* section of a system to calibrate the low-frequency response of the *reproducing* system. (This method can *not* be used for high-frequency calibration [2].) Despite the availability of this information, many users are neither aware of the sources of error, nor of the

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methods for avoiding the errors. This paper presents more details on the sources of error, and on the practical means for eliminating them.

2. THE SOURCES OF ERROR

2.1 Nonstandard Low-Frequency Equalization

The present (1965) NAB standard for open-reel recording [4] specifies a tape flux characteristic at low frequencies that rises with decreasing frequency, with a slope of 20 dB per decade, starting at 50 Hz and continuing upward without limit; the boost is 10 dB at 16 Hz as shown in the broken line of Fig. 1.

In a practical system the rising of the low-frequency response must be discontinued at some lower frequency, but the NAB standard does not specify this second frequency.

Adherence to the standard is likely to cause low-frequency overloading when recording practical program sources, as pointed out by McKnight [5]. Because the 1965 NAB standard calls for this "bad engineering practice," each recorder design engineer must make his own decision on the frequency at which to discontinue the rising response. Good engineering practice suggests a second low-frequency transition frequency to limit the low-frequency boost to a maximum of about 3 or 4 dB. We have measured a number of popular studio recorders, and we find that they cover the whole range, from a boost which shelves at +3 dB to a boost which is +10 dB at 16 Hz and still rising. Thus despite the existence of the NAB standard, there is no actual standardization of the recorded flux below 50 Hz. This is an inconvenience to all, and a real disaster for those who use cue or other control tones in the range of 16 Hz to 63 Hz.

The IEC standard tape flux characteristic at low frequencies for 380 and 190 mm/s (15 and 7.5 in/s) is simply a constant flux [6]. This provides practical standardization because there is no low-frequency recording equalizer and no low-frequency overload problem. The new NAB standard for cartridge recording [7] also calls for constant flux

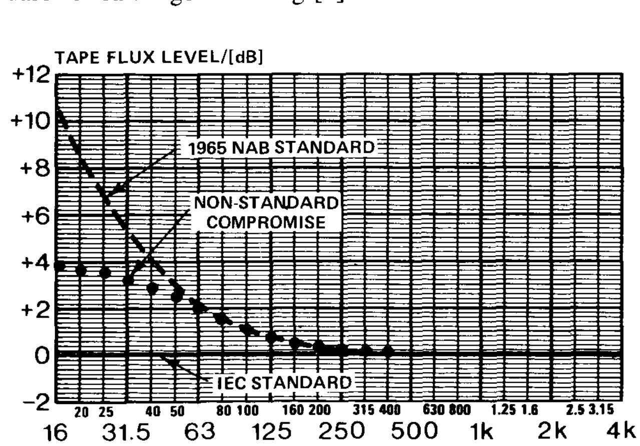

Fig. 1. Tape flux versus frequency. Solid line—IEC standard and 1975 NAB cartridge standard; broken line—1965 NAB open-reel standard; dotted line—a nonstandard compromise: 1965 NAB standard modified by a second transition frequency to limit the maximum boost to +4 dB. (For the latter, the actual transition frequencies are boost from 80 Hz and cut from 50 Hz.)

at low frequencies. We believe that this will also be incorporated into a planned revision of the 1965 open-reel standard.

2.2 Fringing at Long Wavelengths

If the recorded track width is greater than the reproducing head core width, "fringing" will occur at medium to long wavelengths. When full-track calibration tapes are used on multitrack reproducers, a measurement error results. At 1000 Hz it is about 0.4 dB at a speed of 380 mm/s, or 0.8 dB at 760mm/s. [1] The error may increase up to a total of several decibels at lower frequencies.

Similarly, if the recorded and reproduced tracks are of the same general format (say two-track), but not of exactly the same width or location, fringing still occurs if the recorded track width exceeds the reproducing core width. In some systems the recording head is intentionally made wider than the reproducing head. In this case some reproducing fringing is a normal part of the system, and therefore a correction should not be applied for the fringing from a full-track calibration tape.

In other systems the recorded track may be narrower than the reproducing core width. In this case, the response is correct—there can be no fringing. But there will be sensitivity level errors in some circumstances. This occurs because the calibration tape is usually recorded to a specified flux per unit recorded track width (fluxivity) ϕ/w, in webers per meter; but the reproducing head senses the total flux ϕ in webers. The head output is proportional to the total flux, which is the fluxivity times the width: $\phi = \phi/w \times w$.

For example, suppose that a reproducer has a track width of 2.1 mm, and suppose that the reproducer sensitivity (gain) is set with a recorded fluxivity of 200 nWb/m, recorded on a track whose width is 2.1 mm. This gives a total flux of 200 nWb/m × 2.1mm = 420 pWb. Now if the same fluxivity (200 nWb/m) is recorded on a narrower track, say 1.9 mm, the total head flux will be only 200 nWb/m × 1.9 mm = 380 pWb. Therefore when the recorded track is narrower than the reproducing head core, the relative response will be correct, but the same recorded fluxivity will give less total flux, by the ratio of the track widths. Therefore the reproduced flux for these particular dimensions will be reduced to 1.9/2.1 = 380/420 = 0.90 times the original flux, which corresponds to a level reduction of 0.9 dB.

There are two obvious solutions to the fringing problem: either provide fringing correction factors with the calibration tapes, or provide calibration tapes actually recorded in the multitrack format. Unfortunately both of these solutions have shortcomings.

[1] In other words, a reference fluxivity tone of 185 nWb/m that is *not* corrected for fringing plays back about the same level as one of 200 nWb/m that *is* corrected for fringing. Calibration tape manufacturers are not consistent in this matter. MRL tapes are all full track; they are fringing-corrected in 12.5–50-mm widths, but *not* in 6.3-mm width. By contrast, Ampex tapes are partly multitrack format, and partly full-track *not* fringing corrected. Thus there is opportunity for confusion both within the products of one manufacturer, and between the products of different manufacturers—an area needing industry standardization??

2.2.1. Fringing Corrections

The fringing corrections have been calculated by McKnight [8] based on a simplified theory suggested by Grimwood *et al.* [9]; these corrections have been included in the MRL calibration tapes. Further work on fringing by van Herk [10] includes the effect of the head-field's falling off at the edge of the core. The equations of [8] and [9] overstate the amount of fringing by about 0.2 dB to 0.7 dB. Van Herk's formula [10] should be used in place of McKnight's [8].[2]

An even more significant error in the fringing calculations has been reported by Melis and Nijholt [11]. They show experimentally that although the theory is accurate for the region above the undulations in the frequency response (say above 125 Hz at 380 mm/s), at the lower frequencies where the response undulates, the *fringing correction itself* undulates, and the fringing sometimes actually causes a *decrease* in the measured flux, instead of the expected increase. Fig. 2 shows our measurements which confirm Melis and Nijholt's conclusions. For this particular reproducing head the difference between the measured fringing and the calculated fringing (Fig. 2**c**) is about −3.5 dB at 40–50 Hz, and +1.5 dB at 16 Hz at 380 mm/s. This error is due to the simplified geometry used for the fringing calculations. All authors have assumed that the head length is infinite, but in practice the longest wavelengths are longer than the head length. Thus in practice the error is completely dependent on the individual design of the reproducing head. Therefore for the very low frequencies even van Herk's fringing corrections are not valid—not only may the amplitude be wrong, but the *sign* of the correction may be wrong.

2.2.2 Use of Multitrack Calibration Tapes

Multitrack calibration tapes have the economic disadvantage of requiring the manufacture, distribution, and purchase of many different calibration tapes—one for each track configuration for each tape width, as shown in Table 1.

Worse yet, as Table 2 shows, the track widths for a given configuration on 6.3-mm-width tape are not standardized in practice, despite the existence of published standards. For example, we would need three "full-track" tapes and three "two-track" tapes if track mismatch and fringing effects were to be completely eliminated in 6.3-mm tapes.

Thus multitrack tapes are not a satisfactory solution to the fringing problem, both because of the nonstandardization of the actual head core widths and because of the economic disadvantages of manufacturing and purchasing calibration tapes for all the formats.

[2] We have programmed van Herk's formula for an HP-97 calculator. A copy of this program is available from us. Include a blank card if you want a copy of the recorded program. Alternately, an "eyeball" comparison of van Herk's graphs with McKnight's graphs shows that the error is reduced to about ± 0.2 dB if we empirically scale the wavelength by 1.6 times. In McKnight's equation the term f is replaced by $1.6f$. The fringing level at any given frequency will therefore be less than that which the unmodified equation would give.

2.3 Number of Frequencies on the Calibration Tape

Because the low-frequency response of the recording and reproducing systems, once calibrated, is normally quite stable, only a few low-frequency test tones are usually desired on a general-purpose calibration tape. For instance, the MRL calibration tapes provide tones at the octaves—31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, etc., as required by the IEC standard [6]. In the region from 250 Hz to 8 kHz this octave spacing is very satisfactory, because the reproducer response is flat or gradually sloping. But below 250 Hz the reproducer response begins to undulate (this is called the "head bumps" or "contour effect"). The broken curve of Fig. 3 shows measurements of a professional reproducing head for a 16-track 50-mm tape-width recorder. This response is a matter of the reproducing head design [12]; it is characteristic of each head and shield design and beyond the control of the user.

Measurement of this undulating response with only a few frequencies is almost certain to give misleading results. The solid curve of Fig. 3 shows the apparent response from using only the octave frequencies, and the broken curve shows the actual response. One solution to

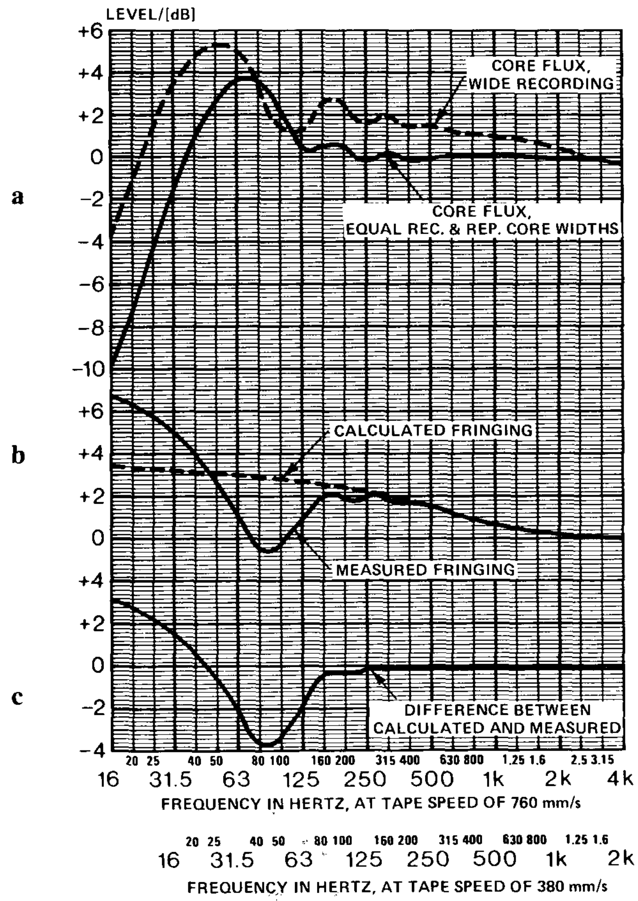

Fig. 2. Fringing in a 16-track system of 1.8-mm-wide tracks on a 50-mm-wide tape. **a**. Measured reproducing head core flux. Solid line—with recording core width equal to reproducing core width, therefore no fringing; broken line—with a wide recording, therefore with fringing. **b**. Measured fringing response (difference between curves of **a**, solid line) and calculated fringing response (broken line). **c**. Difference between measured and calculated fringing.

this problem is to use a calibration tape with many spot frequencies—say six per octave. The three octaves between 31.5 and 250 Hz would require 18 tones, and at 10 seconds per tone this test would run 3 minutes. Such a calibration tape would have use in the laboratory, but would be prohibitively time consuming for most practical calibrations.

The other solution is to use a slowly swept frequency. Such a test signal has been provided on some commercial German calibration tapes [13]. "Slow" is required because the undulations in the reproducing head response are caused by in- and out-of-phase fluxes in the head core, from the tape fluxes on the incoming and outgoing sides of the head. When the sweep is more rapid, the wavelengths are different on the two sides of the head, and the apparent frequency response will be different from that measured with fixed frequencies.

Practical readout of a swept-frequency signal requires an automatic level recorder. (A frequency-tracking automatic level recorder such as the UREI model 200 with model 2010 level and frequency detector is especially convenient.) This is an excellent method, but level recorders are not commonly available in recording studios. Thus this method is of limited practical usefulness.

3. SOME PRACTICAL SOLUTIONS

The best solution for many casual users may simply be to ignore the problems entirely. The audibility of the differences in tape recording and reproducing system responses below 125 Hz may often be obscured by differences in response between various loudspeakers and their associated room acoustics. The meticulous users will surely object: the response errors in one generation of recording might be inaudible, but they will certainly cause problems in multiple generations through the same recording and reproducing system. Furthermore, the errors of response will be increased by companding systems (noise-reduction systems such as Dolby, dbx, Burwen, etc). And finally, systems using low-frequency control tones will certainly have problems. Can a practical solution be found to eliminate all these errors at once? Yes—and it can be summarized as follows.

1) Decide exactly what low-frequency recording equalization you want to use, and modify all recorders to this equalization characteristic.

2) Standardize the widths of the head cores, and thereby the widths of the recorded and reproduced tracks in all of your recorders and reproducers. Also, be sure all head heights are correctly set, so the tracks will be correctly located.

3) Calibrate the reproducers against the now calibrated recorders by recording and reproducing. Slowly sweep the frequency to determine the maxima and minima of response, and set the reproducer low-frequency equalization for the flattest average response.

Here are the details.

Table 1. Track Configurations.

Tape Width /[mm]	Number of Tracks Used	Number of Configurations
6.3	1, 2, 3, 4, 8	5
12.5	2, 3, 4, 8	4
25	4, 8, 16	3
50	16, 24	2

Table 2. Track widths used commercially on 6.3-mm-width tape.

Number of Tracks	Track Width /[mm]	Used By
1 "Full track"	5.9	Ampex
	6.1	NAB standard; Nortronics
	6.3	MRL calibration tapes
2 "Two track"	1.9	Ampex
	2.1	NAB standard; Nortronics
2 "Stereo"	2.8	Studer

3.1 Standardize the Low-Frequency Recording Equalization

At long wavelengths (low frequencies) the recorded flux is directly proportional to the recording current [1], [2]. Thus if you standardize the recording-head current versus frequency, you have also standardized the recorded tape flux versus frequency, and you can use this standardized recorded tape flux to standardize the reproducing system equalizer.

But which low-frequency equalization characteristic? If all your recorders and reproducers are of the same make *and model*, you may simply want to adopt the manufacturer's standard, whatever it is. If you must interchange between different makes or models, measure the recording response of the recorders as manufactured. The details of several measuring methods are given in the Appendix. If all your units are alike, decide if *you* like the manufacturer's choice of low-frequency preemphasis. If you find several different responses, decide which one best serves your purposes. Then modify all your recorders to the response you have chosen.

Personally, we prefer the "flat low end" standardized by IEC [6] and NAB [7]. No recording equalizer (with its precision components) is required at all; you will have no low-frequency overload problems; and you can easily modify any professional recorder to this response simply by using the modification in the machine manufacturer's

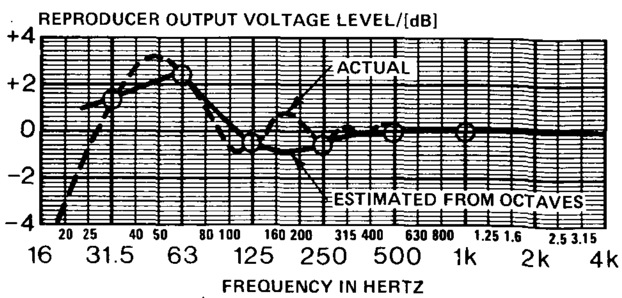

Fig. 3. Effect of measuring response of a reproducer only at octave frequencies. Solid line—response estimated from octave frequencies; broken line—actual response.

instruction manual for the IEC (also known as CCIR) low-frequency response for the recorder and for the reproducer.

3.2 Standardize Track Widths

If you are buying a new system, this is comparatively easy—use the same make and model of recorder throughout your system. You will probably not find it easy to get track-width information from literature or salesmen. Most people do not even know that the track widths are not actually standardized. You may have to measure the track width yourself. Buy a "scale loupe" (otherwise called a "measuring magnifier" or "pocket comparator") from a mechanical-inspection equipment dealer (they cost about 25 $). On many heads you can directly measure visually the width of the recording- and reproducing-head cores. Sometimes, however, the mounting or the intertrack shields or the head case can make it very difficult to locate the edges of the cores. In this case it may be easiest to record a high-level, medium-wavelength signal, "develop" the magnetic image[3] to make it visible, and measure the width of the developed image with the scale loupe.

Be sure that all your recording heads and reproducing heads are set to the proper height. If the recorded track and the reproduced track do not coincide exactly, fringing will occur even though the head core widths are identical. This fringing in reproduction will cause errors of apparent recorded fluxivity and errors of apparent frequency response. These will cause miscalibration of the reproducer, which in turn will cause errors of the actual fluxivity and frequency response of the recorder, when it is calibrated against the reproducer.

If you find that you must interchange recordings made with different track widths, be prepared to accept 0.5–2-dB differences in reproduced levels between the different recorders and reproducers if the recorded track is sometimes narrower than the reproducing head core, or differences in frequency response (due to fringing) if the reproduced track is sometimes narrower than the recording head core.

For stereo recording the European "stereo" format with 2.8-mm track width (used, for instance, by Studer) seems to us to be optimum. It gives about 1.5-dB signal- to noise-level improvement over the 1.9-mm "two-track" heads, and it has a very small fringing effect when reproducing a full-track calibration tape. The disadvantages are that it requires an especially wide erasing head (usually a full-track erasing head is used) and that it has somewhat increased cross talk.

3.3 Calibrate the Reproducers

Having now standardized the low-frequency recording equalization and the track widths, you can calibrate the reproducing systems against the recording systems. Record and reproduce similtaneously; sweep the frequency slowly from the lowest frequency of interest (16 Hz? 31.5 Hz?) up to 1000 Hz. Find the frequencies and amplitudes of the response maxima and minima; then adjust the reproducing low-frequency equalizer for "optimum flatness." We personally prefer to set the low-frequency maxima to be not more than +1 dB and let the minima fall where they may.

This method of setting the reproducer response against the recorder response is recommended by most professional recorder manufacturers in their instruction books. But many users still seem to be unaware of the method, or of the reasons for using this method. The machine manufacturers do not, however, mention the lack of low-frequency equalization standardization or the lack of track-width standardization.

Some systems utilize machines which reproduce *only*, and do not record at all. In principle any reproducing head can be connected to an appropriately designed recording amplifier and used to make its own test recording. In practice this is usually not very convenient. It is more practical to calibrate the reproducer at low frequencies by recording the low-frequency slow sweep on whatever recorder is normally used to make the recordings which this reproducer plays. (We now assume that that recorder has the same track width as this reproducer.) In this case an automatic level recorder is almost a necessity for plotting the reproducer's response.

3.4 Calibrate the "Calibration Tape"

Now that both the recording and the reproducing systems are calibrated to the "optimum" response, you can reproduce your commercial reproducer calibration test tape and measure and write down *its* response. These readings provide a "custom calibration" for this calibration tape on your particular reproducing system, to correct for all the effects we have discussed: variations in the standard equalization, track width, and fringing, and the response at the test frequencies on the calibration tape. Now this "custom calibrated" reproducer calibration test tape can be used to calibrate any other identical type of reproducer. It can also be used in the future to recalibrate the original reproducer, which might in the meanwhile have been unintentionally misadjusted.

APPENDIX A

MEASURING THE LOW-FREQUENCY RESPONSE OF THE RECORDER

The low-frequency response of the recorder will be identical to the recording-head signal-current response [1], [2]. The measurement presents two practical problems, first sensing the recording head current or field, and second eliminating the bias current or field which would otherwise mask the signal.

A1. Means for Sensing the Head Current or Field

The best means for a particular recorder will depend on the particular circuitry of that recorder. Here are several possible alternative methods:

1) Use a "clip on" current sensor around a recording head

[3] Ampex "Edivue Kit," part 50 495-02 (particles, diluent, and a jar); Columbia Magnetics "Magna-See" (particles and diluent in a metal can); Nortronics "Mag View" (spray can—easier to use, but does not seem to give as good an "image").

lead. Check the frequency response of the sensor: many models of current sensors have a restricted range and are not flat over the range of 16–1000 Hz.

2) Some recorders provide a test circuit for measuring recording equalization by substituting a load resistance in place of the recording head (which is itself resistive and inductive). The voltage across this test resistor is proportional to the recording head current. Fig. A1 shows the circuit used with the Ampex 300 and 350, and Fig. A2 the circuit used in the Scully 280-B.

3) Many recorders have a "bias calibration" resistor in series with the return lead of the recording head, as shown in Fig. A3. The audio signal voltage across this resistor is a measure of the head audio signal current. Some recorders have externally available test points across this resistor. Some recorders have a switch which connects the voltage across this resistor to the volume indicator meter, in a "bias test" position. You can then connect an external meter across the meter terminals, which are always easily found.

4) In any recorder, you can sense the recording head *field* directly, rather than sensing the driving current. This method corresponds to the "flux-loop" method used to test reproducing systems. Another head can be placed "gap to gap" with the recording head, and used to pick up the field from the recording head. An integrating amplifier following the pickup head can be used to produce a voltage which is proportional to the recording field versus frequency. This method completely avoids the necessity of electrical connections to the recorder. Fig. A4 shows a possible circuit.

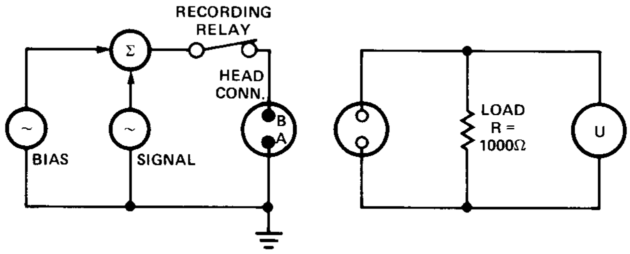

Fig. A1. Recording response measured by unplugging recording head, substituting load resistor, putting recorder in recording mode, and measuring voltage U across resistor. Bias must be removed (see A2). Used with Ampex 350, for instance.

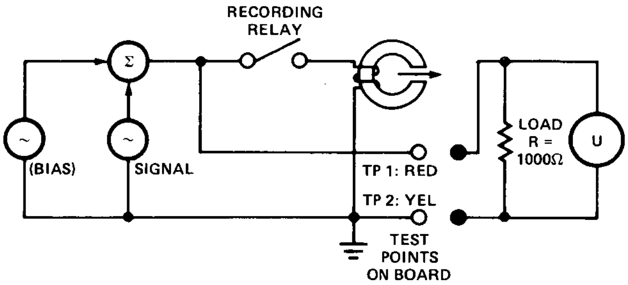

Fig. A2. Recording response measured by method of Fig. A1, in a different circuit configuration. Used with Scully 280-B. The test points are before the recording relay; therefore it is not necessary to be in recording mode, so there is no bias to eliminate.

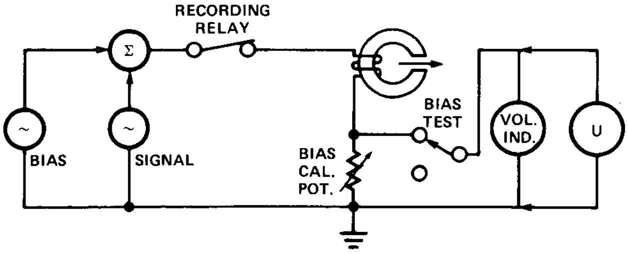

Fig. A3. Recording response measured by measuring voltage U across the current sensing resistor (bias calibration pot).

A2. Means for Eliminating the Bias Current or Field

The high-frequency ac biasing current or field is of greater amplitude than the signal current or field. Therefore the bias must be removed before the signal can be measured. Here are some ways to do it.

1) Disable the bias source. Pull out the bias oscillator tube or disconnect the power supply lead (often easily done by temporarily removing a series resistor from a board), or disconnect the signal feed to the bias oscillator or buffer amplifier. (Because the test circuit in the Scully 280-B works while the recorder is not recording, there is no bias to eliminate in that system.) All recorders have a bias amplitude control, but it usually has a very limited control range—it will reduce the bias current, but not eliminate it completely.

2) Filter out the bias frequency. Measure the audio signal with a frequency-selective meter (wave analyzer or spectrum analyzer). Lacking a frequency-selective meter, filter out the bias frequency with one of the circuits shown in Fig. A5: **a**—use a shunt capacitance across the meter input; set $X_c = R$ at say 4000 Hz; **b**—use a trap tuned to the bias frequency; **c**—use a low-pass filter. This is especially easy with the head-field sensing method shown in Fig. A4—set C to resonate with the pickup-head inductance at say 2000 Hz, and set R for a Q of about 0.7.

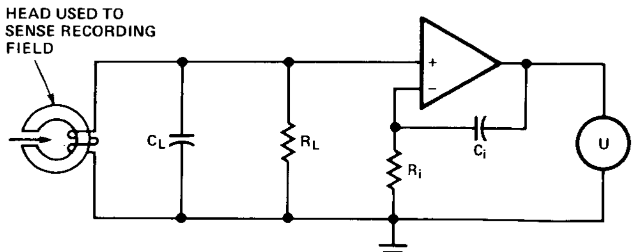

Fig. A4. Recording response measured by sensing the recording head field with another head, filtering out the bias with a low-pass filter consisting of head inductance L, and R and C; then integrating this voltage.

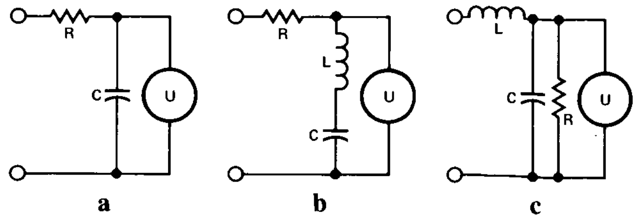

Fig. A5. Several possible means of eliminating the bias. **a**. Low-pass filter, RC. **b**. Tuned bias trap. **c**. Low-pass filter, RLC.

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Mr. McKnight's biography appeared in the December 1977 issue.