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GAP-LENGTH RESPONSE IN MAGNETIC REPRODUCERS: CALCULATION, MEASUREMENT, AND COMPENSATIONS

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GAP-LENGTH RESPONSE IN MAGNETIC REPRODUCERS: CALCULATION, MEASUREMENT, AND COMPENSATIONS

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Gap-length response S(x) is approximated within 1% by $S(x) = \sin \pi x/\pi x$, where $x = 1.11\, \ell_g/\lambda$, ℓ_g = mechanical (optical) gap length, λ = wavelength, and $x < 0.5$. Alternately, the gap length is calculated from the measured null frequency f_n at the speed v; then $\ell_g = 0.8795\, v/f$. Gap-length response compensation is required by standards, but often neglected in practical professional reproducers. Compensation is easily achieved with an RLC "peaking" circuit.

0. HISTORICAL INTRODUCTION

The frequency response curve of a basic magnetic recorder without equalizers shows rather large high frequency losses. There are many causes for these losses (McKnight [1], Bertram [2]), but probably the best-known and the first-explained of these is the gap-length response of the reproducing head. Some authors have even attributed all of the losses in magnetic recording systems to the gap-length loss. But--in fact--the usual design precedure for a magnetic recorder is to choose a reproducing gap length such that the gap-length loss at the shortest wavelength (that is, the highest frequency at the slowest speed) is no more than about 2- to 5-dB.

The gap-length loss formula was first derived for optical (motion picture) recording in the year 1930 by Cook [3]:

$$f(x) = \sin \pi x/\pi x \tag{1}$$

where $x = \ell_g/\lambda = \ell_g f/v$, ℓ_g is the slit width, λ is the signal wavelength, $\lambda = v/f$, v is the film speed, and f the frequency.

When Lübeck studied magnetic recording with gapped ring heads in 1937 [4], he found that the gap loss in magnetic recording was the same as the scanning loss in optical recording, and he arrived at essentially the same response formula. This equation was used in magnetic recording design for many years. In the late 1940's Daniel and Axon [5] found that the measured gap-length response did not agree with this equation. The frequency for null response corresponded to ℓ_g/λ of approximately 0.85, rather than 1.00 as predicted by equation (1). But when the null-response wavelength was measured and used in the equation in place of the gap length, the measured and calculated responses agreed rather well. From this, the concept of "effective gap length" arose, being in fact another name for the measured null wavelength. The assumption or implication, or both, was that the gaps were somehow mechanically imperfect.

In 1952 Westmijze [6] proved that equation (1) given by Lübeck is only a first approximation to the true gap-length response equation. The true equation is very complicated, and Westmijze tabulated a few values calculated from the true equation. In 1961 Fan [7] derived another gap length response formula which he thought to be more accurate because it included the permeability of the tape, but a review of Fan's derivation by Lindholm [8] in 1975 showed that Fan's formula is based on a false premise. Fan's formula is unfortunately incorrect; it should not be used.

Lindholm [8] recently found that the gap-length response can be calculated within 1% for all ratios of gap length to wavelength, $x = \ell_g/\lambda$, by using a simple combination of formulas as given below in eq (2).

1. CALCULATION OF THE GAP-LENGTH RESPONSE

Gap length response can best be calculated* from Lindholm's equations [8]:

$$S(x) = \begin{cases} \sin 1.11\pi x / 1.11\pi x & x < 0.5 \\ 0.326\, x^{-2/3} \sin \pi (x + 1/6) + 0.056\, x^{-4/3} \sin \pi (x - 1/6), & x \geq 0.5 \end{cases} \quad (2)$$

where x is $\ell_g/\lambda = \ell_g f/v$, ℓ_g is the mechanical (optically measured) gap length, and λ is the recorded wavelength, f is the frequency, and v is the tape speed.

A graph of the gap length response is given in Fig. 1. Table 1 shows the key to the curves: given the tape speed v and the gap length ℓ_g, find the number of the applicable curve of Fig. 1b.

2. MEASUREMENT OF THE GAP LENGTH

The gap length may be determined from information supplied by the head manufacturer, by optical measurement, or by measurement of the gap null frequency.

Sometimes the gap length is known (at least approximately) from the head manufacturer's catalog value, or from the tape recorder manufacturer's literature, or by inquiry to the recorder manufacturer's engineering department.

A direct optical measurement is also possible. The gap must be mechanically clean: some tapes cause "gap smear"--they pull some of the core material at the gap edge across the gap, which makes the optical gap length appear to be smaller than the true gap length. For the

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*A program with these equations for Hewlett Packard model 97 calculator is available. Send a self-addressed stamped envelope for a copy of the program: also include a blank card for a copy of the recorded program.

short gap-lengths common for slower speeds (10 µm and less), a high-power microscope (1000 to 2000 power) is required. A split-image eyepiece attachment is a necessity for accurate measurements of short gaps. A suitable metalurgists microscope with attachments cost about 2500 $.

Some gap materials contrast with the laminations, and can be easily seen: for example, a metal head with a copper, mica, or paper spacer. Some materials have the same color and texture as the laminations and may be almost impossible to see: for instance, a metal head with a silver spacer.

If a microscope is not available, it may be possible instead to measure the gap null frequency by recording at the slowest speed on the recorder on which the head is mounted. The principle is simple: Record and reproduce, sweep a sine wave frequency upward until a null in the output is found--that is to say, a minimum output with increasing response at greater and lesser frequencies. This is the null frequency f_n. The gap length is simply calculated [8] then from

$$\ell_g = 0.8795\ v/f_n \tag{3}$$

where v is the tape speed.

In practice the null frequency usually occurs at a frequency which is outside the recorder's normal frequency and wavelength bandpass, and a more complex procedure is required. This is described in Appendix A.

3. GAP LOSS COMPENSATION

In order to standardize the response of reproducers it would be necessary either to standardize on one gap length for all reproducers, or else to compensate each reproducer for whatever gap loss it introduces. All standards of IEC, NAB, RIAA, EIA, and most standards of SMPTE, use the latter approach: the flux recorded on the tape is standardized, and whatever gap loss is introduced by reproducing head is to be compensated by an equalizer in the reproducing amplifiers.

Despite this standard practice, many professional audio reproducers are not equalized for gap loss. Therefore, when they reproduce a calibration test tape which has been recorded to the standard, they show a high frequency droop when the adjustable mid-frequency equalizer is set for flat response in mid-band. This is shown in Fig. 2, solid curve, for a 4 µm gap length, and 190 mm/s tape speed. If the equalizer is re-adjusted for -1 dB at 16 kHz, there is a mid-frequency boost of 1 dB as shown in Fig. 2, dashed curve. Some reproducer calibration tapes (for instance, some of those of Ampex and STL) are recorded with at least a partial compensation for the gap-length loss built into the calibration tape. Other calibration tapes (for instance, those of MRL) do not have any gap-length loss comp nsation built in. These differences are of course seen as differences between the calibration tapes from these different manufacturers.

Gap loss compensation is provided, for instance, in the Ampex Models MR-70 and AG 440 C; 3M Model 79; and Studers. Some other professional audio recorders, however, do not provide any gap-loss compensation. This may or may not cause appreciable errors in response, depending on the reproducing gap-length and the tape speed: the Scully 280 B recorder does not use a gap-loss equalizer, but its 2.5 µm gap length only introduces a 1 dB gap loss at 16 kHz and 190 mm/s tape speed.

4. GAP LOSS COMPENSATION CIRCUITS

The gap-loss response curve can be fit almost exactly up to losses of 10 dB or more by a resonant circuit, or a 2-pole low-pass filter with the proper Q. A more complicated equalizer may also be used. For instance, aperture equalizers may be designed which provide the correct frequency response, but do not introduce phase shift which some users find undesirable. Two mathematical functions which have been used are cosine y, and $\sin^2 z$.

The first practical choice to be made on a multi-speed reproducer is whether to use a switchable gap loss equalizer which is set to compensate the gap loss correctly for each speed. Alternatively, it is cheaper to use a single fixed equalizer if one speed is used primarily: equalize for that speed, and let the other go as it may; or else use a compromise equalization which over-compensates at the high speed and under-compensates at the low speed. Any of these is better than providing no gap-loss compensation at all.

The simplest equalizer is achieved by tuning the reproducing head inductance with a parallel capacitance, and damping the resonance with a resistance, as shown in Fig. 3. Because of stray capacitances and the effective resistance due to eddy current losses of the head, the response of a practical reproducer is much more easily measured than calculated. This equalizer is not easily switchable for several speeds because the low level of the signals at this point, and the consequent sensitivity to hum and other noises. But it is a simple fixed equalizer for one speed, and is so used in some tape recorders, such as for instance the Ampex 440 C.

Another type of equalizer is the low pass filter. This was used for instance, on the Ampex MR-70. The circuit is shown in Fig. 4. In these days an active op-amp low pass filter would probably be used.

Yet another configuration is at RLC "peaker" as used in the 3M Model 79, and shown in Fig. 5.

5. DESIGN PROCEDURE

The practical limitation on the amount of gap-loss compensation to be applied is the accuracy with which the gap length itself is known--both the accuracy of measurement of the gap length, and the manufacturing variability from one head to another having nominally the same gap length. If we suppose, for instance, that the gap length is 12% less than that assumed, then the gap-length response will be in error by the amount shown in Table 2.

TABLE 2: ERROR IN GAP-LENGTH RESPONSE CAUSED BY A GAP-LENGTH WHICH IS 12% LESS THAN THAT ASSUMED

$x = \ell_g/\lambda$	0.25	0.315	0.40	0.50	0.63	0.71
Calc. gap loss/[dB]	1.1	1.8	3.0	4.9	8.7	12.2
Error if 12% short/[dB]	0.2	0.4	0.6	1.1	2.2	3.5

Having chosen the largest value of gap-length to wavelength ratio, x, which is to be compensated for, go to Table 3 which shows the equalizer resonance frequency and the Q to be used for the low pass filter design.

TABLE 3: GAP-LOSS COMPENSATION WITH A LOW-PASS FILTER: VALUES FOR RESONANCE FREQUENCY AND "Q"

Max. ℓ_g/λ compensated	0.28	0.36	0.40	0.50	0.55	0.63
Max. loss comp./[dB]	1.0	2.0	3.0	5.0	6.0	9.0
$f_o = rv/\ell_g$, where r =	0.45	0.55	0.63	0.63	0.70	0.70
Q	1.00	1.25	1.60	1.80	2.24	3.16
$f_{max} = mv/\ell_g$, where m=	0.315	0.44	0.56	0.56	0.67	0.70
Max. rise @f_m/[dB]	1.3	2.6	4.5	5.3	7.0	10.0

Note that for a low-pass filter with a Q of less than 10, the resonant rise level of 20 log Q occurs at the resonance frequency f_o, but the maximum rise is somewhat greater (as shown in Table 3), and occurs at the slightly lower frequency of f_{max}. Only for Q of 10 or more is the resonance rise level equal to the maximum rise, with both occurring exactly at the frequency f_o. Thus the values for f_o and Q should be used in the filter design equations, but the f_{max} and maximum rise level values should be used for tuning and measuring the filter.

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APPENDIX A: MEASURING THE GAP NULL FREQUENCY

First estimate the null frequency, which can be calculated from $f_n \cong 0.9\ v/\ell_g$. For many studio recorders a 3- to 5-µm (120 to 240 microinch) gap length is typical for the reproducing head. In this case, the null frequency at 190 mm/s is approximately 28- to 56-kHz, or at 95 mm/s, approximately 14- to 28-kHz. Another way to estimate the null frequency is to assume that it may be about 1.5- to 3- times the maximum frequency given in the frequency response specifications for the slowest speed of the recorder.

The maximum frequency usable for gap null frequency measurements is usually limited by the frequency response of both the recorder and the reproducer. The recorder bandpass is often limited by an input transformer and by the shape of the recording equalizers. Since the equalizers cause a boost in high frequencies up to approximately the highest frequency transmitted by the recorder, the response of the equalizer usually falls off above that frequency. Also, because of the recording equalization high frequency boost, the tape is easily saturated at high frequencies and you get a form of distortion known as "bias birdies". Furthermore the bias used in direct recording causes a reduction of the flux at short wavelengths, compared to an unbiased recording.

The reproducing head is often resonated at a frequency slightly above the maximum bandpass. This causes the frequency response of the reproducer to fall very rapidly above the bandpass. To minimize all of these effects use the following method:

(1) Disconnect the recording and reproducing heads from the normal electronics, and connect them directly to the test equipment as described below.

(2) Record a satuation flux without bias, by connecting the recording head directly to a sine wave oscillator current source. Since most oscillators are voltage sources, a series resistance is necessary to simulate a current source. If the recording head inductance is known, set the series resistor to approximately 5 times the maximum impedance of the head ; this is approximately 30 times the expected null frequency times the head inductance. As a verification, measure the voltage across the head from approximately 10 kHz upwards. It should rise 20 dB per decade up to a frequency about twice the expected null frequency.

(3) Connect the reproducing head directly to a buffer amplifier, using the shortest possible leads to avoid loading the reproducing head and producing a consequent loss at high frequencies. If the reproducer has an input transformer, do not use it--the high frequency losses are too great. It is desirable to check the frequency response of the system with a flux loop. The output from the amplifier should rise approximately 20 dB per decade to at least twice the expected null frequency.

(4) Make a recording on the best quality, thin-coat tape available. A wide-band instrumentation tape such as Ampex 797 works especially well.

(5) At a speed of 190 mm/s, start recording at a frequency of 10 kHz; at a speed of 95 mm/s or less start recording at a frequency of 5 kHz. At the starting frequency, increase the oscillator output until you get a maximum signal output from the reproducing head. As the input signal amplitude is increased, the output signal should at first increase, then come to a maximum, and finally decrease. Be sure that the head azimuth is set correctly between the recording and reproducing heads. Increase the frequency, observing the output waveform and amplitude on an oscilloscope. Readjust the input signal amplitude as you go to higher frequencies, to give maximum output amplitude at the higher frequencies. Then increase the frequency and search for a minimum in the output signal amplitude. An automatic level recorder used with a very slow sweep is especially useful for this measurement, to see that an actual null has been reached. This null will be the gap null frequency that you are seeking.

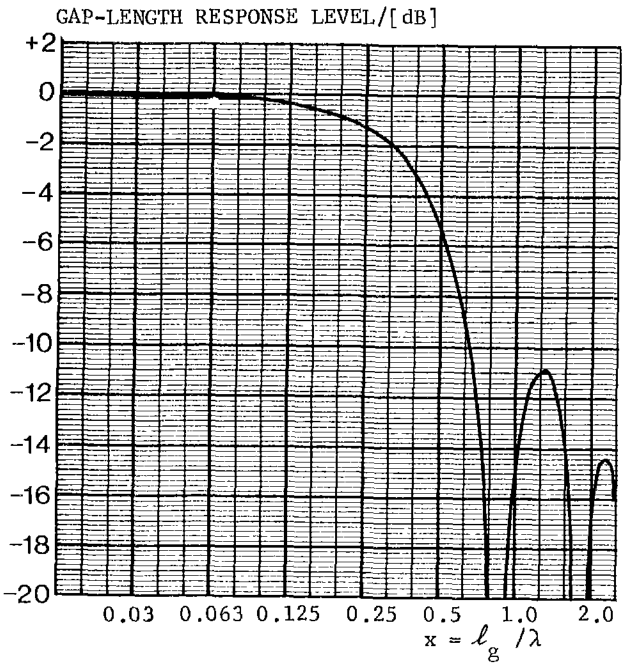

Fig. 1a Gap-length response level versus ratio of gap length to wavelength, x, from eq (2).

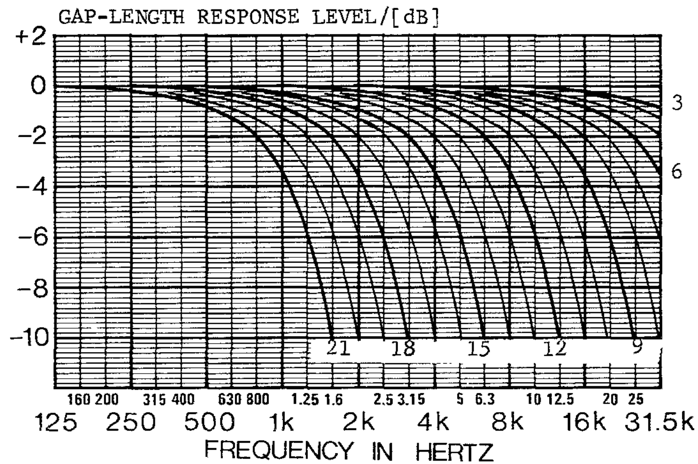

Fig. 1b. Gap-length response level versus frequency, from eq (2). See Table 1 for key to curves.

TABLE 1: KEY TO CURVES OF FIG. 1b. From tape speed and gap length find number of applicable curve.

TAPE SPEED/ [mm/s]	([in/s])	MECHANICAL GAP LENGTH/ [μm] ([microinches]) 1.0 (40)	1.25 (50)	1.6 (63)	2.0 (80)	2.5 (100)	3.15 (125)	4.0 (160)	5.0 (200)	6.3 (250)	8.0 (315)	10.0 (400)	12.5 (500)	16.0 (630)	20.0 (800)	25.0 (1000)
24	(0.94)	11	12	13	14	15	16	17	18	19	20	21	-	-	-	-
48	(1.88)	8	9	10	11	12	13	14	15	16	17	18	19	20	21	-
95	(3.75)	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
190	(7.5)	-	3	4	5	6	7	8	9	10	11	12	13	14	15	16
380	(15)	-	-	-	-	3	4	5	6	7	8	9	10	11	12	13
760	(30)	-	-	-	-	-	-	-	3	4	5	6	7	8	9	10

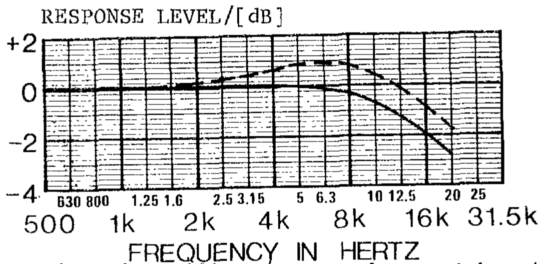

Fig. 2. Gap loss in a 190 mm/s reproducer with a 4 μm gap length. Solid curve: The uncompensated gap loss causes a droop of 2 dB at 16 kHz when a standard recording is played. Dashed curve: If the reproducer transition frequency is changed from the standard 3150 Hz (50 μs) to 2800 Hz (57 μs), 16 kHz response is brought to -1 dB, but a 1 dB mid-frequency rise results.

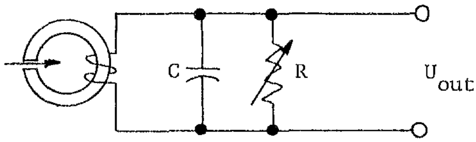

Fig. 3. Gap-loss compensated by resonating the reproducing head with capacitor C, and damping the resonance with resistor R. Used on Ampex 440 C.

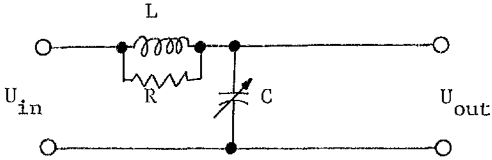

Fig. 4. Gap-loss compensated by a passive low-pass filter, R,L,C. Used on Ampex MR-70.

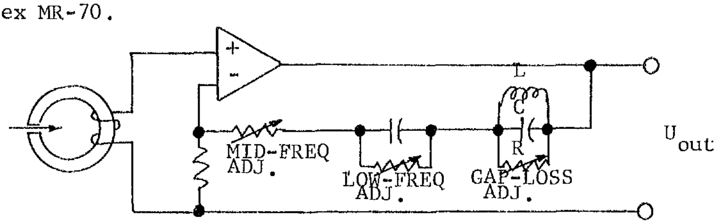

Fig. 5. Gap-loss compensated by a "peaking" circuit R,L,C, in the pre-amp equalizer feedback loop. Used on 3M Model 79.