Gap-length Response In Magnetic Reproducers: Calculation, Measurement, and Compensation[1]

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Gap-length response S(x) may be approximated within 1% by S(x) = sin(1.11πx)/1.11πx, where $x = \lambda_1/\lambda$, λ_1 is the measured gap-response first-null wavelength, λ is the wavelength, and $x < 0.68$. The first-gap-null wavelength can be calculated from the first-gap-null frequency f_n at the tape speed v as $\lambda_1 = v/f_1$. Methods for measuring the first-null frequency are described here in detail.

When using a typical modern tape with relative permeability $\mu_r = 2$, the first-null wavelength can be calculated from the mechanical (optical) gap length ℓ_g as $\lambda_1 = 1.12\ \ell_g$.

Gap-length response compensation is required by magnetic recording standards, but often neglected in practical professional reproducers. Compensation is easily achieved with a two-pole low-pass filter (for instance, an RLC "peaking" circuit). A program for computing the optimum design parameters of the filter is described, and is available.

0 INTRODUCTION

The wavelength response curve of an unequalized magnetic recorder[2] shows rather large short-wavelength (high-frequency) losses. There are many causes for these losses (McKnight [1], Bertram [2], [3]), but probably the best-known and the first-explained of these is the gap-length response of the reproducing head.

Some authors have erroneously attributed *all* of the losses in magnetic recording systems to the gap-length loss. In fact, for good reasons which we will explain later, the usual design procedure for a magnetic recorder is to choose a reproducing gap length such that the gap-length loss at the shortest wavelength (the highest frequency at the slowest speed) is no more than about 2 to 5 dB. Therefore, while the gap loss is usually not negligible, it is certainly not the major short-wavelength loss.

We will review the theory of gaploss, give a correct and practical gap-loss equation, and present practical methods for measuring the gap first-null wavelength or the mechanical (optical) gap length, and for designing a gap-loss equalizer. A small (60 kbyte) computer program is available for calculating the gap-loss response, and designing an equalizer.

1 HISTORICAL REVIEW OF THE THEORY FOR CALCULATING THE GAP-LENGTH RESPONSE

1.1 A Theory for Optical Recording for Motion Pictures

The "aperture loss" (also called "scanning loss") formula was first published for optical recording (motion picture sound on film) in the year 1930 by Cook [4]:

$$G(x) = \text{sinc}\,(x) \qquad (1)$$

where

$\text{sinc}\,(x) = \sin(\pi x)/(\pi x)$

$x = \ell_g/\lambda = \ell_g f/v$ in radians[3],

ℓ_g is the optical scanning slit width,

λ is the signal wavelength, $\lambda = v/f$,

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[1] Originally presented at the 58th Audio Engineering Society Convention, New York, 1977-11, AES Preprint Nr. 1297. Revised more times than you would believe; most lately 2008-08-31.

[2] In practical terms, this means ac-biased recording of a sine-wave signal having a constant current vs frequency, and reproducing the recording with a differentiating (ordinary inductive) head followed by an integrating amplifier.

[3] Since the angle πx is in radians, the calculator, computer function, or table of sines must be for angles in radians.

v is the film speed, and

f is the frequency,

and consistent units are used (for instance, all lengths in meters, and all times in seconds).

Fig. 1 shows a linear-scale plot of this sinc (x) function. It clearly has the shape of a sinusoid divided by the increasing value of x, with nulls at integer multiples of x. At a casual glance, it looks as tho, below the first null, the response simply falls linearly with increasing frequency. (Note that the parameter x corresponds to frequency.) When re-plotted on a log-log (audio) scale, **Fig**. 2, however, the function looks very different: now we see that the response is flat from the lowest frequency ($x \to 0$) up to $x \approx 0.1$, then has an ever-increasing slope until the first null at $x = 1$.

1.2 The First Theory for Magnetic Recording

Lübeck studied magnetic recording with gapped ring heads in 1937 [5]. He found that the gap loss in magnetic recording was similar to the scanning loss in optical recording, and he arrived at essentially the same response formula, Eq. (1) and **Fig**s, 1 and 2, where ℓ_g is now the mechanical gap length of the magnetic head.

1.3 Measurement Does Not Confirm This Theory Very Well

In the early 1950s Daniel and Axon [6] confirmed that the *measured* gap-length response generally followed the shape of Eq. (1), but that there were two systematic differences:

First, the first-null wavelength occurred consistently at approximately $x = 0.85$, rather than at $x = 1.00$ as predicted by Eq. (1). But when the first-null-response wavelength λ_1 was *measured* and used in Eq. (1) in place of the gap length λ_g, 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 first-null wavelength λ_1. (Some others assumed or implied that the longer "effective gap length" was due to gaps that were somehow mechanically imperfect. This was later proven to be incorrect.)

Second, above the first-null, the measured response deviated significantly from Eq. (1): The null frequencies should have been harmonically related, but were not; and the slope of the measured maxima of the response between the nulls did not agree with the slope calculated from Eq. 1.

Daniel and Axon concluded that "The first minimum occurs at a wavelength approximately given by[4] $\lambda_1 = 1.18\ \ell_g$, regardless of the actual value of ℓ_g ." and "Below the first minimum of a ring-type head, the response can be accurately represented by the empirical expression sinc (λ_1/λ) , where λ_1 is the wavelength corresponding to the first minimum."

The German Standard for measuring tape flux (1957 and 1973) [7] subsequently specified using this same gap-response function, sinc (λ_1/λ).

1.4 The Definitive Theory for a Tape With Unit Permeability

In 1952 Westmijze [8], [9] showed that the sinc (x) function of Eq. (1) that had been used by Lübeck and others really applies only for a hypothetical reproducing head in which the tape passes *thru the middle* of the gap, as shown in **Fig**. 3a, from Westmijze, who called this an "infinite gap". Real tape heads of course have the tape passing over the *top* of the gap, as shown in **Fig**. 1b. For this practical configuration, Eq. (1) is a first approximation to the gap-length response equation. Westmijze derived the exact equation assuming a relative tape permeability $\mu_r = 1$. This equation is unfortunately in terms of integrals for which there is no closed-form solution — that is, they must be integrated numerically. Westmijze's Table 1 lists a few 3-digit values computed from the exact equation for x = 0, 0.125, 0.250, ... 3. He also showed that a closed form asymptotic expansion (his Eq. 15a) is within 1 % of the exact equation for values of x greater than 0.5. In 1966 Wang [10] published a more detailed table, again from numerical integration of Westmijze's equation, this time with 4-digit values, with x = 0.01, 0.02, ... 1.25.

1.5 A Simplified Calculation

In 1974 Lindholm [11] needed a closed-form equation for gap loss that would be valid over the range x = 0.01 ... 10.0 . The solution he found was to use a sinc (1.11 x) function for $x < 0.5$, where the constant 1.11 was found by curve fitting to Wang's Table. The fit is excellent: ±0.02 dB. For $x > 0.5$, he should have been able to use Westmijze's Eq 15a, but he found that the response calculated from this equation did not agree at all with the response in Westmijze's Table 1. He found that the coefficient, 0.282, published by Westmijze for the second term in Westmijze's Eq (15a) was much too large: it must have contained a typographical error. Early attempts to recalculate the coefficient were unsuccessful. Therefore Lindholm determined an approximate coefficient, 0.0552, again by curve fitting to Wang's table. Since that time D. L. A. Tjaden of Philips Research Laboratories has redetermined the coefficient [9]. It turned out that a factor of 1/5 had been omitted in Westmijze's publication, and the coefficient should have been 0.056357, not 0.282.

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[4] The symbols and equation have been conformed to those used elsewhere in this paper.

Thus gap-length response for tape permeability $\mu_r = 1$, and for *any* value of x, can be calculated from Lindholm's equations [11], which we have reproduced here as Eq (2).

$$S(x) = \begin{cases} \text{sinc}\,(1.11\,x), \text{ for } x < 0.5 \\ 0.326\,x^{-2/3} \sin \pi(x + 1/6) + 0.0552\,x^{-4/3} \sin \pi(x - 1/6), \text{ for } x \geq 0.5 \end{cases} \quad (2)$$

where x is $\ell_g/\lambda = \ell_g f/v$, in radians,

ℓ_g is the mechanical (optically measured) gap length,

λ is the recorded wavelength,

f is the frequency, and

v is the tape speed,

in consistent units.

1.6 A Further Simplified Calculation

For typical audio applications the wavelength range beyond the first null wavelength is not used at all, so the second part of Eq. (2) is not absolutely necessary. Suppose we were to use only the first part, that is sinc kx, and re-fit this equation to Wang's table, for greater maximum value of x, and a slightly greater error. For $k = 1.120$ and a range of $x = 0 \ldots 0.75$, we find that the error level is still only ±0.12 dB. At $x = 0.75$, the response level is -15 dB, which is already well beyond the practical range of gap equalization, because of the error sensitivity, discussed below in Sec. 3.5.

1.7 A Theory Including Tape With a Permeability Greater Than 1

Bertram and Lindholm have made a further refinement of the gap loss function [12] by adding the effect of the medium permeability[5] and also the head-to-tape spacing. They show [12 **Fig**. 4] that the effect of the permeability of a modern high-loaded coating[6] with a mean permeability of 2, and no spacing, is to increase the ratio of the gap-first-null wavelength to the gap length (λ_1/ℓ_g) by 6 %. That is, for $\mu_r = 1$ (used in Westmijze's calculations), $\lambda_1/\ell_g = 1.14$; and for $\mu = 2$, $\lambda_1/\ell_g = 1.21$. The effect of head-to-tape spacing for this permeability is small and in the opposite direction: it reduces this ratio by about 2 %, back to $\lambda_1/\ell_g = 1.18$, which is 1.18/1.14 = 4 % greater than for a tape permeability $\mu_r = 1$.

They conclude that for the range of practically-encountered analog tape permeabilities ($\mu_r = 1 \ldots 3$) and spacing, one can approximate the gap-loss response by using Eq. (1), and substituting the *first-null wavelength,* for the gap length, by redefining x as λ_1/λ (rather than λ_g/λ).

They also conclude that a wider-range calculation can be made by using Eq. (2), redefining x as $1.04\,\lambda_g/\lambda$.

Thus Bertram and Lindholm have finally verified theoretically Daniel and Axon's conclusions [6]: "The first minimum occurs at a wavelength approximately given by $\lambda_1 = 1.18\,\ell_g$, regardless of the actual value of ℓ_g ." and "Below the first minimum of a ring-type head, the response can be accurately represented by the empirical expression sinc (λ_1/λ), where λ_1 is the wavelength corresponding to the first minimum."

1.8 Comment

Despite the fact that Westmijze published the correct gap loss formula for a tape permeability of 1 in 1953, and Bertram and Lindholm published the correct gap loss formula for a tape permeability of 2 in 1982, you will still find some books that give Eq. (1), based on the mechanical (optical) gap length. They may or may not mention a magical "effective gap length" that is about 14 to 20 % greater than the mechanical gap length.

We now know that one can convert between mechanical gap length and null wavelength by the relation

$$\lambda_1 = 1.18\,\ell_g; \quad (?)$$

that there is a perfectly good theoretical explanation for this apparent discrepancy; and that one can calculate the gap response level either from

$$L_{gl} = 20 \log \text{sinc}\,(\lambda_1/\lambda)$$

or equivalently

$$L_{gl} = 20 \log \text{sinc}\,(1.18\,\ell_g/\lambda).$$

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[5] In 1961 Fan derived a gap-length response formula which included the effect of the permeability of the tape, but a review of Fan's derivation by Lindholm [11] showed that Fan's formula is based on a false premise. Fan's formula is therefore unfortunately incorrect; it should *not* be used.

[6] "Loading" or "packing fraction" in tape design parlance refers to the relative amount (fraction) of magnetic material mixed into the binder.

In this paper, "gap length" with no modifiers always means "optical" or "mechanical" gap length. Then we can use the names "effective" or "magnetic" gap length to describe the effect of the defects in the mechanical construction of practical gaps. The many possible defects are described in the literature — for instance, some are described in §2.2.3.3 and Table 2 of [1], and some others are described in [13].

Note finally that the "effective gap length" may also be *shorter* than the mechanical gap length: with some metal heads, some tapes cause "gap smear" — the tape pulls some of the core material at the gap edge across the gap, which makes the effective gap length *smaller* than the mechanical length of the gap spacer! We have seen the effect with scanning electron microscopy (SEM) photographs, and measured a case with a head whose gap spacer was about 2.6 µm, where the gap-first-null frequency shifted upward by 25 % for the "smeared" gap, relative to the "clean" gap. In this case, the "smeared" gap showed slightly more spacing loss: that is, the response of the smeared gap was first below the unsmeared gap, due to spacing loss; then above the response of the unsmeared gap, due to the decreased effective gap length.

2 DETERMINING THE GAP-FIRST-NULL WAVELENGTH AND THE MECHANICAL GAP LENGTH

In order to design gap-loss compensation (see Sec. 3 below), one must first know the value of the gap length or the first-null wavelength.

Sometimes the approximate mechanical gap length is known 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. This value can be used for an approximate calculation of the gap response, as described above.

For accurate determination of the gap response, the most relevant measurement is that of the gap-first-null wavelength. It is usually possible to measure the gap-first-null frequency by recording at the slowest speed on the recorder on which the head is mounted. The principle is simple: Record and reproduce a variable-wavelength sine-wave signal; sweep the frequency upward until the first null in the output is found — that is to say, the first minimum in the output, with increasing response at lesser *and at greater* frequencies. This is the first-null frequency f_1 in hertz. (If the output does not increase at frequencies *above* the first-null frequency, you don't really know that you have a null.) The gap-first-null wavelength λ_1 in meters is then simply calculated from

$$\lambda_1 = v/f_1 \qquad (3)$$

where v is the tape speed in meters per second. The mechanical gap length may be calculated from this gap-first-null wavelength measurement as

$$\ell_g = 0.85\ \lambda_1. \qquad (4)$$

In practice the first-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 to perform this measurement. This is described in Appendix A.

A direct optical measurement of the gap length is also possible. A comparison of the optical measurement of the mechanical gap length with the mechanical gap length as calculated from the first-null wavelength may be useful to confirm the quality of the gap construction.

For the short gap-lengths (10 µm and less) common for slower speeds, a high-power microscope (1000 to 2000 power) is required for an optical measurement. A split-image eyepiece attachment is a necessity for accurate measurements of short gaps. A suitable metallurgist's microscope with attachments costs thousands of dollars "and up".

Some gap materials contrast with the laminations, and can be seen easily: for example, one can easily see a copper, mica, or paper spacer in a metal head. Other materials have the same color and texture as the laminations and may be almost impossible to see: for instance, a silver spacer in a metal head. Then an optical measurement is difficult-to-impossible.

3 GAP LOSS COMPENSATION

3.1 Gap Loss Compensation and Standards

In order to standardize the response of reproducers it is 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 the reproducing head is to be compensated in the reproducing system by an equalizer for that particular head and speed.

3.2 Gap Loss Compensation on Commercial Tape Recorders and Calibration Tapes

Despite the standard practice just described, many professional audio reproducers are not equalized for gap loss. Therefore, when the adjustable mid-frequency equalizer of such a reproducer is set for flat response in the mid-band, and then this reproducer is used to reproduce a calibration test tape which has been recorded to the standard, the high-frequency response shows a droop. This is shown in **Fig**. 4, 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 results a mid-frequency boost of 1 dB as shown in **Fig**. 4, dashed curve.

Some reproducer calibration tapes (for instance, some of those of Ampex and STL) have been recorded in a non-standard way, with at least a partial compensation for the gap-length loss built into the calibration tape. Other calibration tapes (for instance, those of MRL) are recorded in the standard way, with no gap-length loss compensation built into the calibration tape. Flat response can be achieved with gap-loss compensated *either* in the reproducer (the "standard" way) or in the calibration tape and also in the recorder (the "non-standard" way). When the two systems are mixed, the response of the reproducer to the calibration tape will either rise if the compensation is both places, or fall if it is neither place.

Gap loss compensation is provided, for instance, in the reproducer of the Ampex Models 440 C and MR-70; the 3M Model 79; and Studers. Some other professional audio reproducers, 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 introduces only a 1 dB gap loss at 16 kHz and 190 mm/s tape speed.

3.3 Gap Loss Compensation Circuits

The amplitude response of the gap-loss equalizer curve (the inverse of the amplitude response of Eq. (2)) can be fit almost exactly up to losses of 10 dB by a resonant circuit, or a two-pole low-pass filter, with the proper resonance frequency and Q. We will discuss such an equalizer in some detail. Note, however, that this method of equalization introduces phase distortion, which some users might find objectionable for music recording.

Other equalizer functions might be used instead. For instance, aperture equalizers may be designed which provide the correct frequency response, but do not introduce phase shift. The equalizer response may also be approximated from a manipulation of the infinite series expansion for the sine function or the cosine function. We will not further consider these other possibilities.

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 others go as they will; 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 with a passive low-pass filter, realized by tuning the reproducing head inductance with a parallel capacitance, and damping the resonance with a resistance, as shown in **Fig**. 5. 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 example of a passive low-pass filter equalizer is that used for instance, on the Ampex MR-70. The circuit is shown in **Fig**. 6. In these days an active op-amp low-pass filter could be used instead.

Yet another configuration is an RLC resonant "peaker" as used in the 3M Model 79, and shown in **Fig**. 7.

3.4 Designing a Two-Pole Low-pass Filter as a Gap-loss Equalizer

Intuition suggests that a two-pole low-pass filter with a Q greater than unity has a response that is the right general shape for a gap-loss equalizer: the gap loss is flat at long wavelengths, becoming an increasingly-steep *drop* as the frequency approaches the gap-first-null wavelength; the two-pole low-pass filter is flat at low frequencies, becoming an increasingly-steep *boost* as the frequency approaches the resonance frequency. A series expansion of the sinc (x) function and the inverse of the filter response confirms the similarity of the two. With the right scaling, there should be a match. In fact, in a practical engineering design there are many factors in the equalizer design, so there is not a unique optimum resonance frequency and Q, but many combinations that produce a more-or-less close match over a larger or smaller wavelength and frequency range.

Such a filter can be realized with a comparatively simple circuit whose design formulas are well known. Active filter design is a specialty unto itself, and there are enough books on it to consume your time and money budget for a long time. A good place to start is Don Lancaster's *Active-Filter Cookbook* [14].

We developed a curve fitting program, as follows[7].

The gaploss function used is Eq (2). When the tape speed and gap-first-null wavelength are specified, the function gives a frequency response.

The equalizer function is

$$R(\omega)=1/\sqrt{\omega^4+(1/Q^2-2)\omega^2+1} \tag{4}$$

taken from Lancaster [14] (p 54, **Fig**. 3-13, B) modified slightly for the response as function of $f/f_0 = \omega$, and Q (Lancaster's $d = 1/Q$). When the resonance frequency and Q are specified, this function gives a frequency response.

We assumed an audio-frequency bandwidth, and have made a table of 19 audio frequencies, standard 1/3rd octaves from 1000 Hz to 6300 Hz, and, to have better resolution at the higher frequencies where the slopes become greater, standard 1/6th octaves from 7000 Hz to 20 000 Hz. Two out-of-band frequencies, 22 400 Hz and 25 000 Hz, have been added for the display, so you can see what is happening just above the audio band. The program automatically drops the frequency range by one octave when the gap first-null frequency is less than 12.5 kHz, and two octaves when the first-null frequency is less than 6.3 kHz.

To find an optimum match of the equalizer to the gap loss, we start by setting the Q to 0.707; this is the largest Q for which the equalizer response does not rise above unity gain; at higher Q values, the equalizer response rises at high frequencies.

We assumed that a best fit would be obtained by allowing some positive "ripple" in the equalized response, somewhat like the design of a Chebyshev filter, so a maximum level error must be chosen.

The responses are fitted by the following simple iterative calculation: At each frequency between 1 kHz and 20 kHz[8] the gaploss response and the equalizer response are calculated, then multiplied together, and the response at the frequency at which the response is greatest is stored. Then the stored response is compared with the maximum desired error mentioned above. If the stored value is less than maximum desired, then the Q is increased by 10 %, and the calculation is repeated until the stored value is greater than the desired value. Then this loop is repeated, but each time the Q is reduced by the ripple size, until the stored value is less than the ripple. Finally the Q is increased by half of the ripple, and that is the final value.

Then the input values, the responses, and the net error are displayed, plus some filter test parameters to be described later. An example (a printout of the screen display) is shown in **Fig**. 8. On an old XT computer (8088 CPU), **Fig**. 8 took 2.6 s to compute and display. On a modern computer, the display seems to appear instantaneously.

When you use the program, it first asks you to input the tape speed, then the first-null wavelength. It calculates the first-null frequency, using Eq (3), displays its value, and recommends a resonance frequency that is 75 % of the first-null frequency, and asks for the resonance frequency that you want to use.

We must now take a small but important detour: Three different frequencies are of interest in the design of "resonant" circuits such as this filter, and all of these frequencies are sometimes called "the resonance frequency". The first "resonance" frequency is the undamped *natural* frequency of oscillation, which we call f_0. This is the frequency that is used in the filter design Eq. (4) above (f_0 is Lancaster's $\omega/2\pi$, which he calls the "cutoff frequency").

The second "resonance" frequency is the frequency of maximum response. When the filter Q is very high ($Q >$ 10), the frequency of maximum response is the same as f_0, and the response at this frequency is Q; that is, if the Q is 20, then the response is maximum at f_0, and its value is 20 times the response at a very low frequency.

The natural frequency f_0 is *always* the frequency at which the output of the filter is exactly 90° out of phase with the input, and the response at f_0 is *always* Q times the low-frequency response.

But (and this is why we introduced this section) when tuning a filter, we most commonly measure the frequency of *maximum* response, and the relative response level at *this* frequency. At lower values of Q ($Q < 10$) used in gap-loss

[7] This 60 kbyte program, “GAPEQ.EXE”, for an IBM-compatible computer is available from MRL, at the email address in the title of this paper . The program is written in the "F-PC" dialect of the FORTH language, and the disk includes an executable (turnkey) version of the optimization program. The FORTH source code file, “GAPEQ.SEQ”, and F-PC with software floating-point arithmetic, are also available.

[8] Altho the response at the two highest frequencies is calculated and listed for information, it is not used in the curve fitting.

equalization, the maximum response is *not* at f_0, but at a lower frequency, and the response is *greater* than Q. Thus we use modifications of Lancaster's Eq (D) for the frequency for maximum response:

$$f_{max}/f_0 = \sqrt{1-1/(2Q^2)}$$

and Eq (E) for the response at this frequency:

$$L_{max} = 20 \ \log \ (2Q^2/\sqrt{4Q^2-1})$$

Finally, the third definition of "resonance" is the damped actual frequency of oscillation (frequency of transient "ringing"), which we do not use here at all.

Suppose now that you have built the filter using the natural frequency and Q values as shown, for example, in **Fig**. 8, and you are ready to verify its response. The easiest way is to use the frequency of maximum response and response at the frequency of maximum response (which is *not* the natural frequency), as calculated from formulas given above and listed on the right side of **Fig**. 8. The filter response should correspond to these values. If necessary, trim the filter components to get the correct frequency and level of maximum response.

Now you have completed designing and testing your gap loss equalizer.

3.4 Practical Limitations on Gap Length Compensation

One can fit the low-pass filter response to the gap-loss response almost up to the first null frequency: for instance, one can match the two responses with an error of ±0.5 dB up to a gaploss of 14 dB, which occurs at 85 % of the first-gap-null frequency. But is this practical? The answer is “no”, for the following several reasons.

One practical limitation on the amount of gap-loss compensation to be applied is the accuracy with which the first-null wavelength itself is known. There are limitations to the accuracy of measurement of the first-null frequency and to the optical measurement of the mechanical gap length. In addition, if you have taken the nominal gap length from the head manufacturer's catalog rather than measuring it, there is the manufacturing variability from one head to another having nominally the same gap length.

If we suppose, for instance, that the gap is really 12% shorter than the length assumed, then the values of the first-null wavelength will all be 12 % less than assumed, and the gap-length response at each assumed value of x will be in error by the amount shown in the line "Error", of Table 3. For instance, suppose that you compensate for gap loss up to $x = 0.63$, where the gap loss compensation is 8.7 dB. If, in fact, the gap were 12 % shorter than you supposed, you would have a 2.2 dB error in the response at the assumed $x = 0.63$.

Another limitation is the effect of the permeability of the tape, mentioned above [12]. Since tape permeability values are not usually published, the relationship of first-null wavelength to gap length may have a further uncertainty of about 5 % added to it.

Thus, although it is possible to correct large amounts of gap loss (up to about 14 dB of loss), such a system will have doubtful accuracy at the shortest wavelengths, because even a small error in the gap-first-null wavelength or in the filter tuning produces a large error in the compensated response. A 3 % error in determining the gap length — and even 3 % is difficult to achieve in practice — will cause a 1.7 dB error in the response.

4 SUMMARY

to be written

APPENDIX A: MEASURING THE GAP-FIRST-NULL FREQUENCY AND WAVELENGTH

First estimate the first-null frequency, which can be calculated from $f_n \approx 0.84\ v/\ell_g$. 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 first-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 first-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.

If you try to use a professional audio recorder electronics to measure the gap first-null, you will usually find that the maximum frequency usable is limited by the frequency response of both the recording electronics and the reproducing electronics:

The recorder bandpass is often limited by an input transformer, which acts as a low-pass filter. It is also limited by the shape of the recording equalizer: the gain of the equalizer usually increases with frequency up to approximately the highest frequency transmitted by the recorder. Above this frequency, the gain of the equalizer usually decreases. Also, because of the high frequency boost of the recording equalization, the tape is easily saturated at high frequencies. This causes a form of intermodulation distortion known as "bias birdies": as you *increase* the input frequency beyond a certain frequency, you hear and see on an oscilloscope an output frequency that *decreases*, caused by a beating of the input signal and the bias frequency. Furthermore the bias used in direct recording causes a reduction of the tape flux at short wavelengths, compared to the short-wavelength tape flux from an unbiased recording.

The reproducing head is often resonated at a frequency slightly above the maximum bandpass specified for the tape recorder. This resonance is used variously to compensate for eddy-current losses in the head core; to compensate for the gap loss at one speed; and to limit the reproducing system's bandwidth in order to reduce out-of-band noise, bias pickup, etc. This resonance causes the frequency response of the reproducer to fall very rapidly above the bandpass.

The standard audio reproducing electronics contains a (more-or-less) integrating network that increases the level of low-frequency signals relative to high-frequency signals. This is necessary for the standard frequency response, but it reduces the signal-minus-noise level of the high-frequency signal at the gap-null frequency, and makes it more difficult to find that frequency.

To minimize all of these problems 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 saturation flux *without bias*, by connecting the recording head directly to a sine wave current source. Since most oscillators are voltage sources, a "voltage-to-current" converter of some sort is required. Voltage-controlled current sources (VCCS) are described in operational-amplifier books [15]; a power op-amp is usually necessary. Alternatively, one can simulate a current source by using a voltage amplifier in series with a resistance. 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 first-null frequency in hertz times the head inductance in henries. As a verification, measure the current thru the head from approximately 10 kHz upwards. The current should be constant up to a frequency about twice the expected first-null frequency. The measurement of the head current can be performed with an ac ammeter whose response is flat over the desired frequency range; or by measuring the voltage drop across a resistor in series with the head. It is also usually valid to measure the voltage drop across the recording head, which should rise 20 dB per decade up to a frequency about twice the expected first-null frequency. The caveat is that the head must be mainly an inductive reactance over this frequency range. The ultimate test is that the output voltage from a flux loop over the recording gap should rise proportionately with frequency.

(3) Connect the reproducing head directly to a flat-response buffer amplifier (do not use an integrating amplifier) that has a high input impedance compared to the head impedance at the expected first-null frequency. Use the shortest possible leads to minimize capacitive loading of the reproducing head, since capacitance produces a resonance, then a loss, at high frequencies. Even if the reproducer normally uses an input transformer, it is probably better not to use it — the high frequency losses are usually too great. It is also 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 first-null frequency. (We say "approximately" because the eddy-current losses in the head will cause some droop from the 20 dB per decade rise, but it doesn't matter because we are only looking for the *frequency* of the null.)

(4) Make an *unbiased* recording on the best quality, thinnest-coat tape available. For gap lengths of 3 to 4 µm or less, it is necessary to use a short-wavelength "logging" tape such as Ampex 705. Other possible tapes would be a wide-band instrumentation tape such as Ampex 799. "Digital audio" tape such as 3M 275 or Ampex 467 also have thin coatings, but their high coercivity requires high fields for recording and especially for erasing.

(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, then finally decrease. Be sure that the head azimuth is set correctly between the recording and reproducing heads. Otherwise you may measure the *azimuth* null frequency: it is also a sinc (x) function! Increase the frequency, observing the output waveform and amplitude on an oscilloscope. Re-adjust the input signal amplitude as you go to high frequencies, to give maximum output amplitude at the higher frequencies. Then increase the frequency and search for a minimum in the output signal amplitude. This null will be the gap-first-null frequency that you are seeking, f_1. Insert this and the tape speed into Eq. (3), and you will get the desired gap-first-null wavelength λ_1.

Even tho you follow all of these steps, you still may not be able to find a first-null. A common problem especially with recording- and reproducing-electronics that are mounted in the same chassis is the crosstalk of the recording signal directly into the reproducing system. This crosstalk is usually capacitive, so it increases with frequency; therefore it is difficult to tell whether a signal that falls in level then increases is a null in the reproduced signal, or merely a continuously falling reproduced signal combined with rising crosstalk. The phase between the crosstalk and the desired signal varies with the signal frequency, and also randomly because of flutter. This phase change causes a signal level fluctuation that looks just like "dropouts" of the recorded signal.

It is sometimes possible to reduce the crosstalk: if it is due to capacitive coupling in the wiring, electrostatic shields or re-routing of the wiring may reduce the crosstalk. More usually the crosstalk is direct inductive coupling between the recording head and the reproducing head. Moving the heads farther apart from each other would be effective, but is not usually mechanically possible. Magnetic head shields do help, especially a front cover on either or both the recording and the reproducing heads. If the crosstalk still masks the reproduced signal (which is the usual case with short gap lengths), it is necessary to make a recording, rewind the tape, and reproduce the record separately with the recording signal disabled. A very convenient procedure is to record a slow sweep (say 10 kHz to 100 kHz in 100 seconds), turn off the recording electronics, rewind the tape to the beginning of the record, then reproduce the signal and plot it on a level recorder that has a time-synchronized sweep.

Yet another technique that can be used when the tape transport speed is continuously variable is this: Record a constant frequency, say 20 kHz, and *simultaneously* reproduce it (through a bandpass filter if desired to eliminate noise). Start with the speed set at say 190 mm/s, then, *while simultaneously recording and reproducing*, sweep the *speed* downward to slower and slower speeds until you find the gap first-null.

In order to verify that a first-null has been found, you should also find the increasing output at a speed below that at which the signal disappears.

Another limitation on the measurement of the gap-first-null frequency — especially with wider heads (for example, full-track, 6.3 mm width) — is the effect of tapered gaps. Daniel [6] has shown that a tapered gap with its gap centerline parallel to the tape flux direction has a response minimum, but no null.

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CAPTIONS

Fig. 1 Shape of the pole pieces P, and relative position of the gap ℓ and an element of tape T for the two types of head discussed. a) The hypothetical "infinite" gap (tape passes *thru the middle* of the gap), for which Eq. (1) applies; and b) the "semi-infinite" gap of a practical head, for which Eq. (2) applies.

Fig. 2 Gap-length response level versus *x*, the ratio of gap length to wavelength; from Eq. (2).

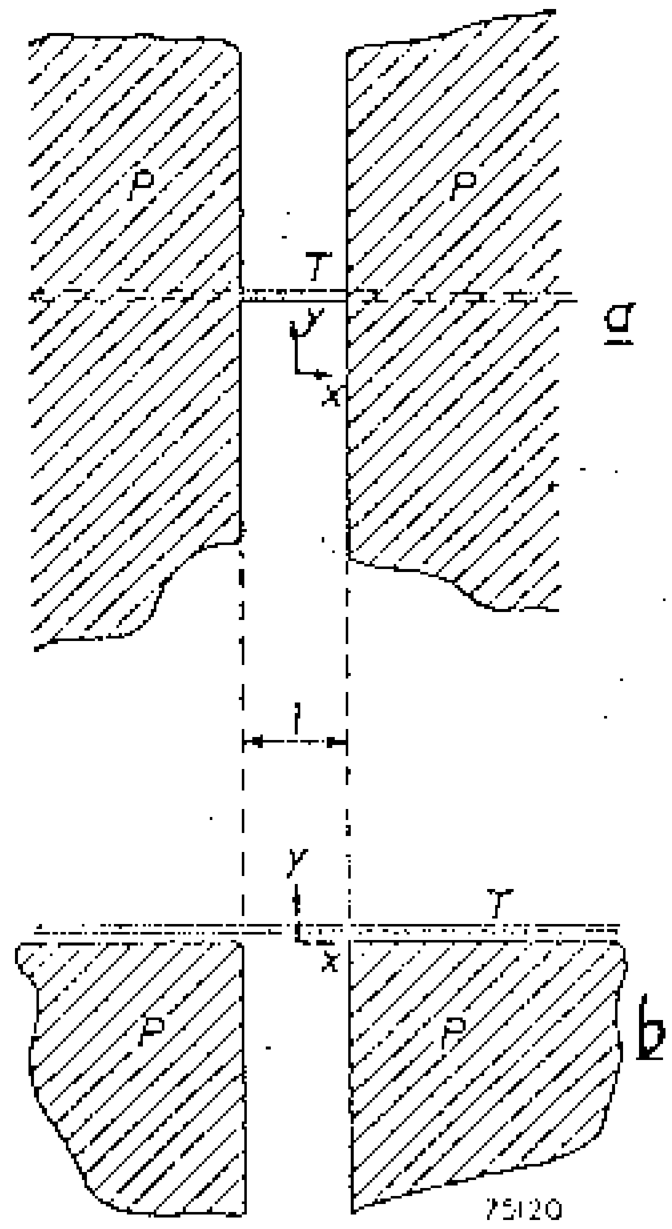
Fig. 3 Gap-length response level of **Fig**. 2, replotted onto a frequency scale. Each of the numbered curves is for a different gap-length and speed combination, as shown in Table 1.

Fig. 4 Gap loss in a 190 mm/s (7.5 in/s) reproducer with a 4 µm gap length, playing an IEC2 (NAB) Calibration Tape. Solid curve: The reproducer equalization has been set for the standard 3150 Hz transition frequency. The uncompensated gap loss causes a droop of 2 dB at 16 kHz. Dashed curve: The reproducer equalization has been adjusted from 3150 Hz to 2800 Hz, bringing the 16 kHz response up to -1 dB, in trade for about a 1 dB response rise between 4 and 9 kHz.

Fig. 5 Example of gap loss compensation as used on the Ampex 440 C: The reproducing head inductance is resonated with capacitor C, and the resonance is damped with adjustable resistor R.

Fig. 6 Example of gap loss compensation as used on the Ampex MR-70: A passive two-pole low-pass filter in the electronics consists of the inductance L paralleled by damping resistor R, resonated by the adjustable capacitor C.

Fig. 7 Example of gap loss compensation as used on the 3M Model 79: A resonant circuit L2-C2, damped by the adjustable resistor R2, is placed in series with the usual integrating capacitor C1.



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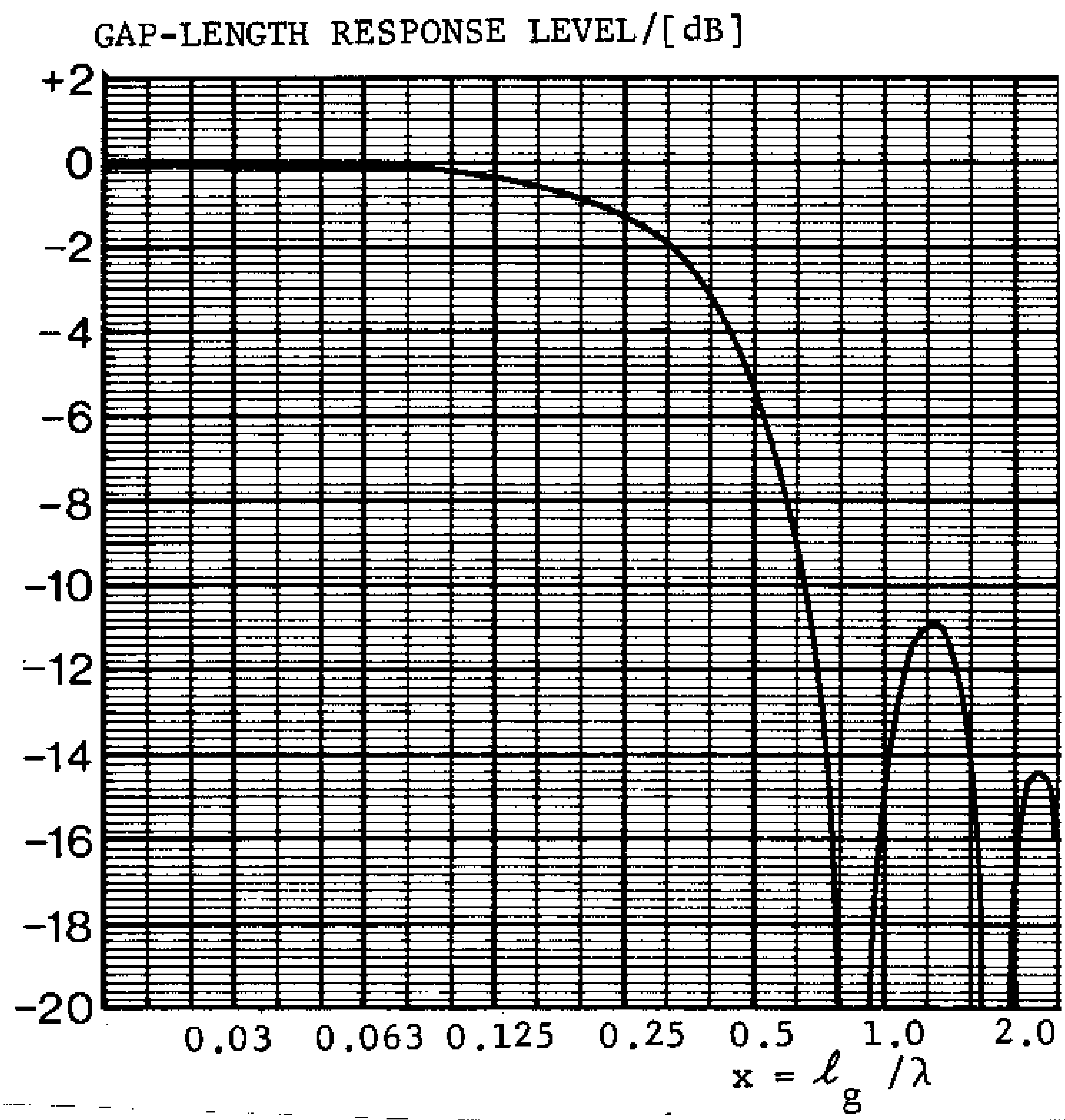
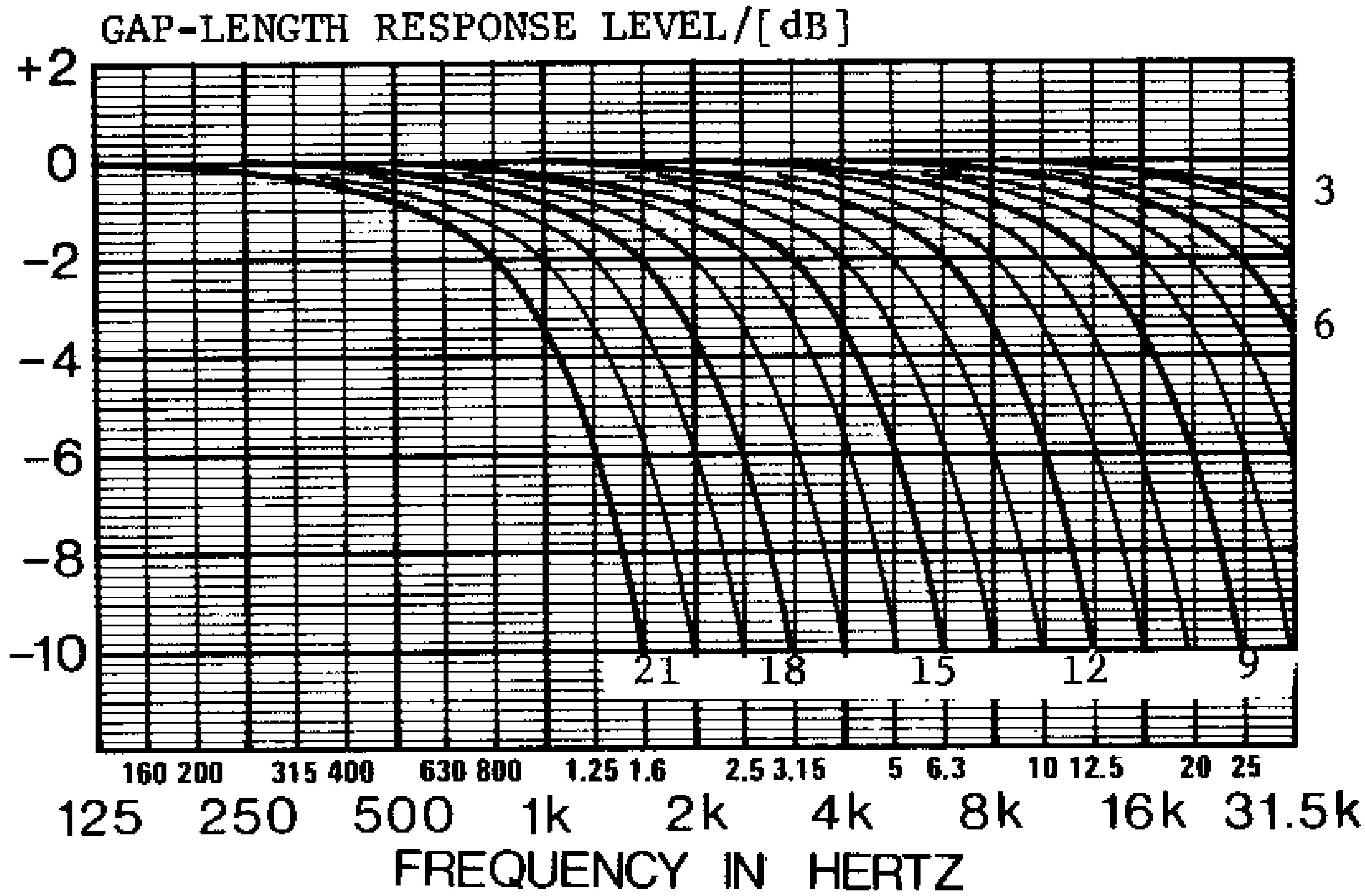


Fig. 2 Gap-length response level versus x, the ratio of gap length to wavelength; from eq (2).



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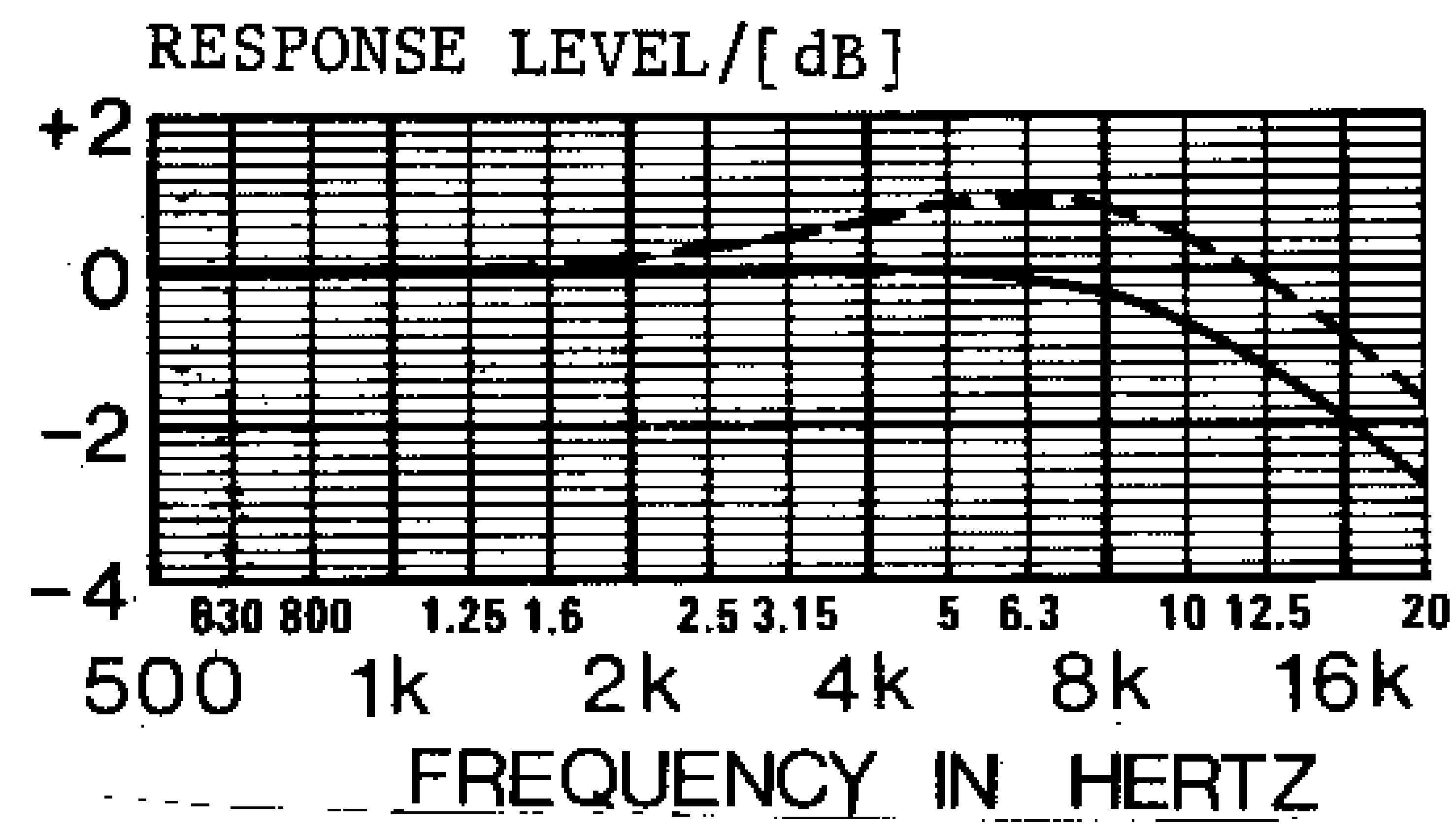

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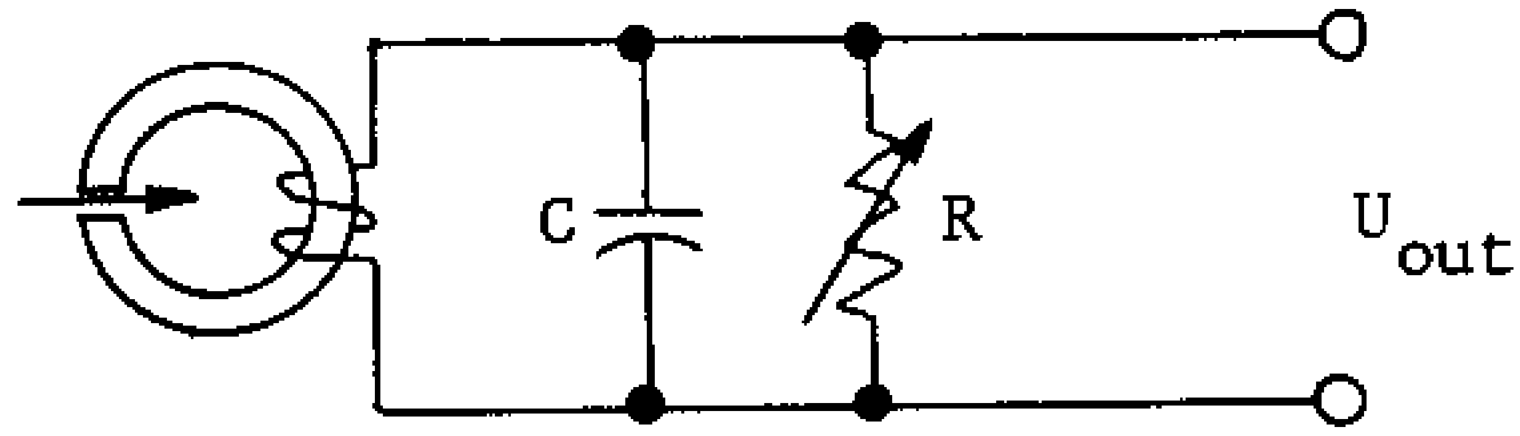
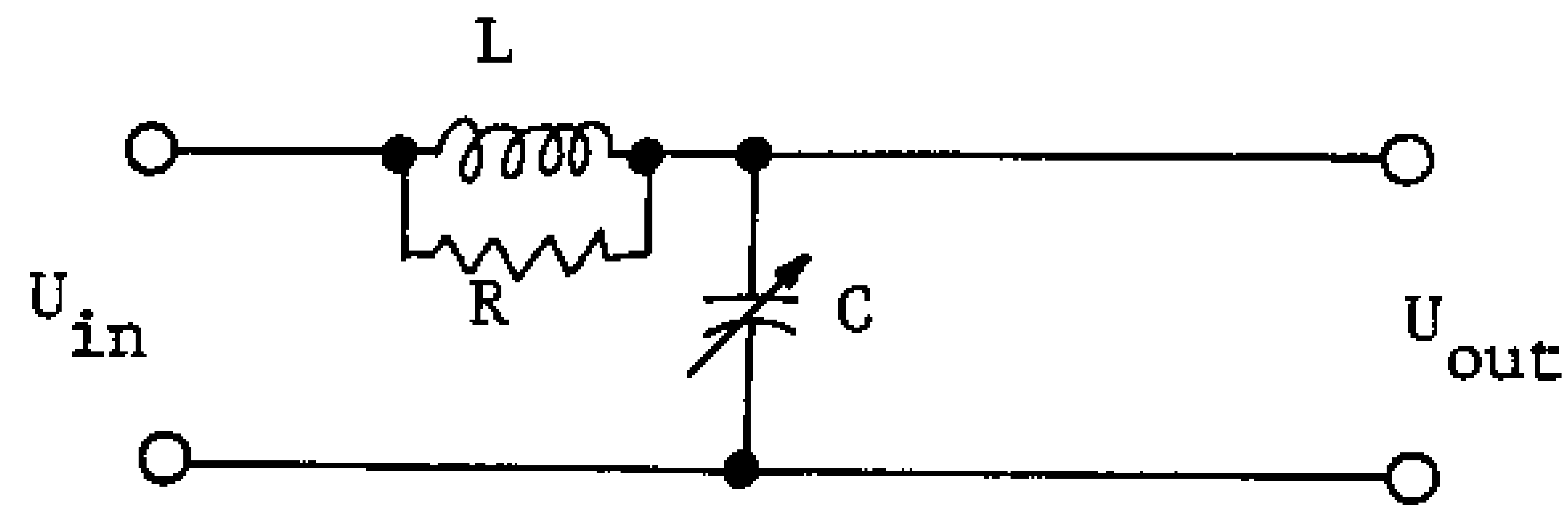


Fig. 5 Example of gap loss compensation as used on the Ampex 440 C: The reproducing head inductance is resonated with capacitor C, and the resonance is damped with adjustable resistor R.



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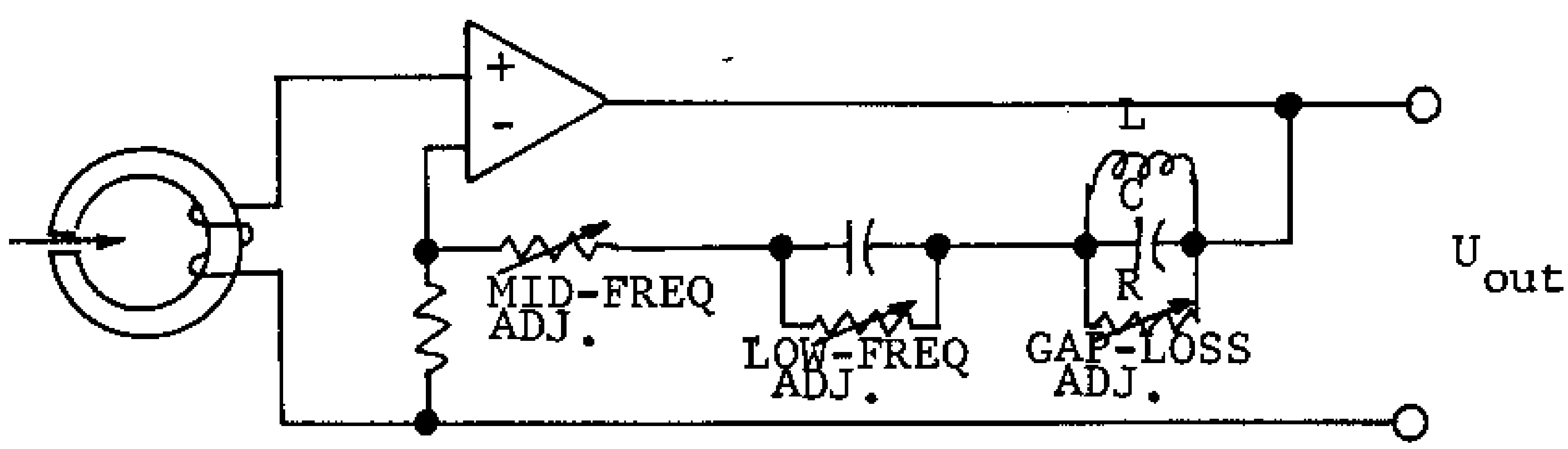

Fig. 7 Example of gap loss compensation as used on the 3M Model 79: A resonant circuit L3-C3, damped by the adjustable resistor R3, is placed in series with the usual integrating capacitor C1.