Dynamic Range Limitations in Tape Recording *

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Limitations are imposed on the dynamic range of a tape recording by the type of tape, track width and tape speed. Dynamic range will decrease as tape speed decreases, and as track width decreases; the style of tape will also control dynamic range. Equipment can limit the maximum signal by adding amplifier distortion, by incorrect bias, or by introducing even-order distortion from magnetized heads or unsymmetrical bias. Misalignment of track height between recording and reproducing heads can degrade the dynamic range. The common noise contributors are: dc noise from magnetized heads or unsymmetrical bias; noise caused by too low a bias frequency; modulation noise (both AM and FM), and reproducing head and amplifier noise. It is, however, perfectly feasible to build a recorder that poses no practical limitation to dynamic range. Even with low-noise tapes and narrow track widths, the noise is limited by the tape itself.

FOR the purpose of this paper, dynamic range will be defined as the ratio between the maximum output signal and the noise, expressed in db. It is an experimentally verified fact that audio recording is often carried to the saturation flux of the tape; therefore, the "maximum output" signal will be taken as tape saturation. It is impossible to express the dynamic range of a tape recorder with one number because both tape saturation and tape noise vary with frequency. We therefore plot dynamic range as a function of frequency, using noise density (i.e., noise power per cps of bandwidth) in place of wideband noise. (Noise power per cps is measured with a narrowband wave analyzer of known bandwidth, then converted to power in a one cps bandwidth by subtracting from the noise reading the quantity 10 log bandwidth [in cps] of the analyzer.)

The plot of dynamic range *vs* frequency is a useful tool, but even it falls short of completely specifying the system performance. It does not indicate the signal-handling capabilities of the tape system adequately, since it gives no information about the amount or type of distortion that occurs between the saturation and the noise. Our current signal-to-noise specification gives the wideband noise below the 3% harmonic distortion level; this specification too fails to indicate the signal handling capabilities, and tells nothing about the ceiling or saturation of the system.

Signal handling varies widely between tapes. As an example, 3M No. 111 tape has a "3% distortion-to-saturation" ratio of 8½ db while 3M No. 120 high output tape has a ratio of 6½ db. If operating level is established with an Ampex Standard Tape, 3M No. 111 tape will have approximately 0.8% third harmonic distortion at operating level, while No. 120 will have 0.25%. System nonlinearity will also vary widely with frequency because of short wavelength saturation and because of the presence of recording pre-emphasis at the low- and high-frequency ends of the spectrum. This distortion will also vary with the type of tape being used.

A reasonable description of system performance can be obtained by plotting saturation, response and noise density as a function of frequency. Figures 1, 2, and 3 show ex-

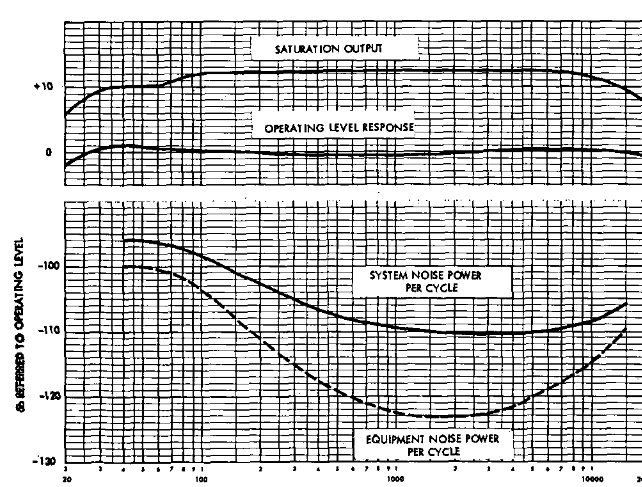

FIG. 1. Plot of 15 ips saturation, response, and noise density as a function of frequency. (Full track, 3M 203 tape. Data taken on an Ampex MR-70 tape recorder using NAB equalization, 150 kc bias, and a 234-mil wide reproduce head with 180 μin. gap.)

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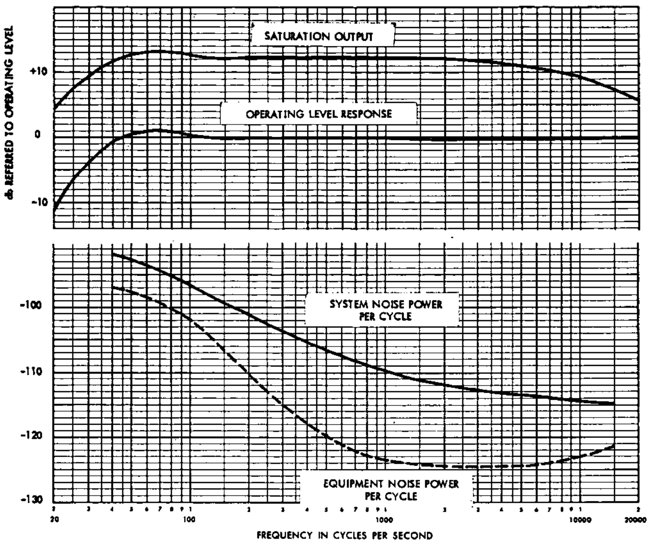

FIG. 2. Plot of 30 ips saturation, response, and noise density as a function of frequency. (Full track, 3 M 203 tape. Data taken on an Ampex MR-70 tape recorder using 17.5 μsec post-emphasis and no low-frequency pre-emphasis, 150 kc bias, and a 234 mil wide reproduce head with 180 μin. gap.)

amples of three such curves, for 7½, 15, and 30 ips. In this discussion on the limitations of dynamic range, it will first be assumed that the tape recorder has no effect on the performance;[1] under this condition, the dynamic range will vary only with track width, tape speed, and the type of tape. Then, the practical limitations that may be posed by the equipment will be discussed. Response should be run at a sufficiently low level to avoid compression. A

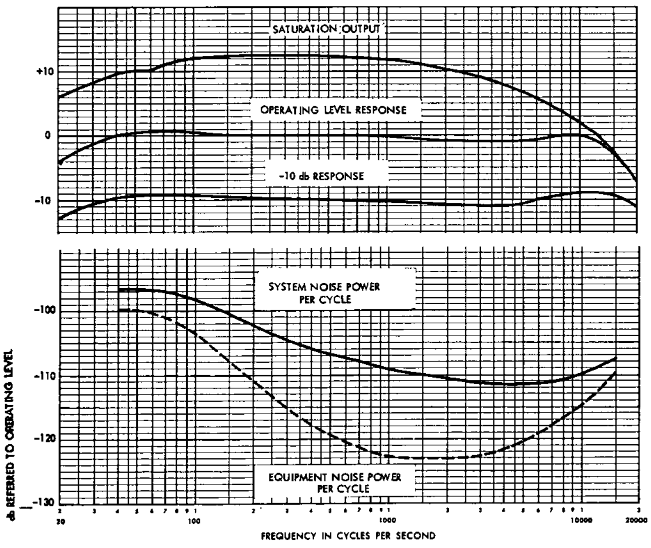

FIG. 3. Plot of 7½ ips saturation, response, and noise density as a function of frequency. (Full track, 3M 203 tape. Data taken on an Ampex MR-70 tape recorder using NAB equalization, 150 kc bias, and a 234 mil wide reproduce head with 180 μin. gap.)

[1] Figures 1, 2, and 3 also show the equipment noise. As long as the equipment noise is 6 db below the tape noise, it will only raise the system noise by 1 db. It can be seen that from 100 cps to 10,000 cps the dynamic range is controlled by the tape.

rough indication of how signal-handling capabilities vary with frequency can be obtained by noting how close the response curve is to saturation at different frequencies. Using a mid-frequency as a reference, if another frequency is 5 db closer to saturation, one could guess the nonlinearities to be 10 db worse than at the mid-frequency, since third harmonic distortion rises with the square of the input signal.[2] Figure 4 is a summary of the data on the previous figures, showing the dynamic range for the three speeds.

Figure 5 shows how the dynamic range varies with track width; the signal is proportional to the track width w and the noise to $\sqrt{w}$. Therefore, the signal-to-noise ratio is proportional to $\sqrt{w}$. Figure 6 shows the variation of dynamic range with type of tape for a regular tape, a high output tape and a low noise tape.

Now, what practical limitations can the recorder pose on the dynamic range? On the saturation end, the most obvious limitation is imposed by the overload characteristics of the recording and reproducing amplifiers. With input

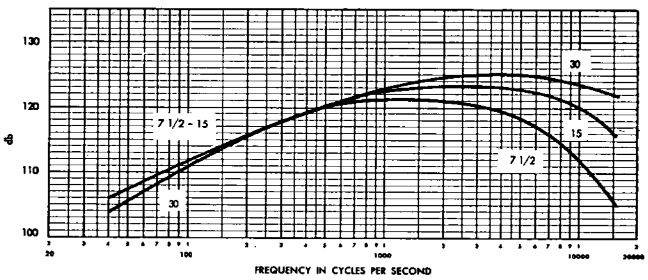

FIG. 4. Dynamic range as a function of frequency for 7½, 15, and 30 ips. (Full track, 3M 203 tape.)

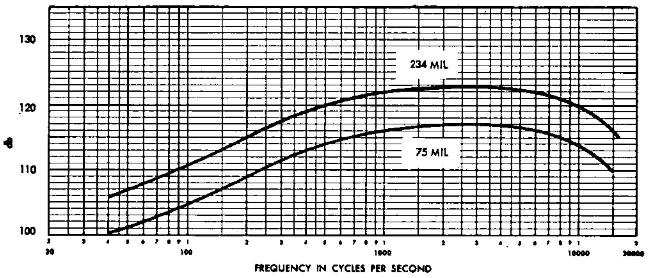

FIG. 5. Dynamic range as a function of frequency for track widths of 75 and 234 mil. (15 ips, 3M 203 tape.)

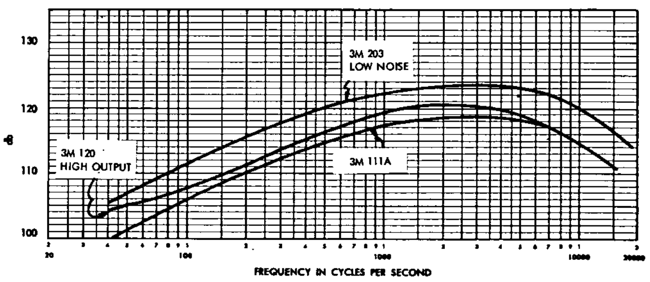

FIG. 6. Dynamic range as a function of frequency for three styles of tape. (15 ips, full track.)

[2] R. Z. Langevin, "Intermodulation Distortion in Tape Recording," *J. Audio Eng. Soc.* **11**, 270 (1963). See especially Fig. 1 of this reference.

signals 20 db above the "operating level" (vu meter zero), the tape has still not reached complete saturation. Music peaks have been measured 26 db above a vu meter zero indication. An amplifier that clips can also generate higher-order distortion products which can be most annoying; this clipping is especially likely when operating in the "red" of the vu meter. Crosstalk in recording and in reproducing, print-through, and insufficient erasure are also obvious offenders.

The magnetic recording process is inherently symmetrical, which means that even-order distortion will not be present. Even-order distortion can be introduced, however, either through even-order distortion in the recording or reproducing amplifiers, or by a dc flux in the recording head due to a magnetized head or asymmetrical bias waveform.[3]

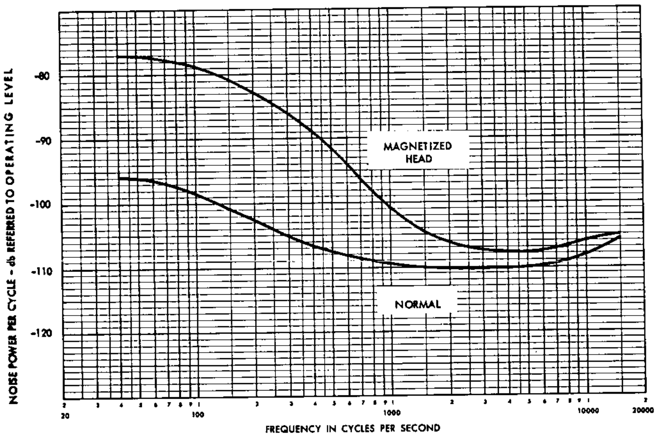

FIG. 7. Noise density as a function of frequency for a magnetized head and a normal head. (15 ips, full track, 3M 203 tape.)

A practical limitation to dynamic range which is not obvious is misalignment between the heights of the recording and the reproducing heads. This can be a particular problem with narrow track-widths. It occurs because the "operating level" of the reproducer is normally set with a full-track standard alignment tape. The recording level is then set to produce the same output as the standard tape. If the track from the recording head misses the reproducing head, it is necessary to record at a higher flux level to obtain the same output from the reproducing head that the standard tape gave. This higher flux level being recorded has a greater distortion than the nominal 1%, thereby reducing the distance to the saturation level. The reproducer still "sees" essentially the same tape noise.

If the bias wavelength is too long (i.e., too low a frequency for a given speed), the noise will increase. At 30 ips, for instance, an increase of bias frequency from 100 kc to 150 kc causes a noticeable reduction of noise.

If the bias amplitude is less than that necessary for maximum recording sensitivity (peak bias) for the tape in use, the distortion increases. This has been discussed in detail in the literature.[4–7]

The system including tape recorder/tape/reproducer may amplitude- and/or frequency-modulate a signal passed through it; the modulation sidebands are often audible, and constitute modulation noise.[8] The modulation noise will usually set the practical limits to the dynamic range *in the presence of a signal.*

AM noise is caused by poor tape-to-head contact and irregularities in the tape. "DC noise" is a form of AM noise which occurs when unsymmetrical bias waveform or magnetized heads or tape guides cause a dc magnetization to be present all of the time.[9] This dc is amplitude modulated, and the audible result consists of pops and crackles plus a general increase in hiss level. Figure 7 shows how a slightly magnetized head can increase the noise. (This magnetization was insufficient to cause erasure of a 1 mil wavelength signal—15 kc at 15 ips—yet the noise increased dramatically.) When an ac signal is recorded, it is similarly amplitude-modulated.[10] The effect is audible mainly with low-frequency signals; it also has the sound of pops and

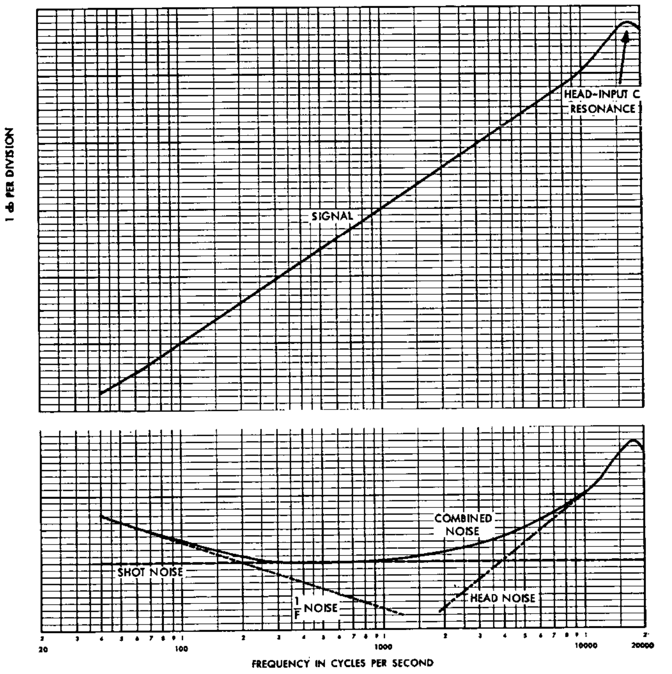

FIG. 8. Signal and noise as a function of frequency from a conventional reproducing head-preamplifier system. (Hypothetical case. All equalization removed.)

[3] *Ibid.* See especially Fig. 2 of this reference.

[4] G. L. Dimmick and S. W. Johnson, "Optimum High-Frequency Bias in Magnetic Recording," *J. Soc. Motion Picture Engrs.* **51**, 489 (1948). See Figs. 2, 3, and 4.

[5] R. Herr, B. F. Murphey, and W. W. Wetzel, "Some Distinctive Properties of Magnetic-Recording Media," *J. Soc. Motion Picture Engrs.* **52**, 77 (1949). See Figs. 1 and 2.

[6] W. K. Westmijze, "Studies on Magnetic Recording," *Philips Res. Rep.* **8**, 148 (1953). See Figs. 33 and 34.

[7] E. Belger and P. Scherer, "Investigations of More Recent Types of Magnetic Recording Tapes," *Rundfunktechnische Mitteilungen* **5**, 193 (1961). (In German) See Figs. 4, 5, 6, and 9.

[8] P. Smaller, "An Experimental Investigation of the Noise in Magnetic Tape Recording which is a Function of the Tape Characteristics," *J. Audio Eng. Soc.* **7**, 196 (1959).

[9] J. W. Gratian, "Noise in Magnetic Recording Systems as Influenced by the Characteristics of Bias and Erase Signals," *J. Acoust. Soc. Am.* **21**, 74 (1949).

[10] D. F. Eldridge, "DC and Modulation Noise in Magnetic Tape," *Proc. Intermag. Conf., IEEE,* T-149 (April, 1963).

crackles. This noise is more noticeable at higher tape speeds.

Frequency modulation with a high modulating frequency (e.g., around 3 kc) is called "scrape flutter"; it is noticed when recording high frequencies, and results in a hiss riding along with the tone.[11]

The reproducing head and preamplifier system is the final offender. The preamplifier usually limits the dynamic range at the lower frequencies. The $1/f$ noise in tubes, resistors, and transistors normally predominates. However, with low-noise tapes it is possible to approach the shot noise in the 200 to 500 cps region. At the extreme high end, the eddy current loss in the reproducing head normally limits dynamic range. Both reproducing head and preamplifier can introduce hum (the power line frequency plus its harmonics) in reproduction.

Figure 8 shows the noise and signal present in a conventional reproducing head plus preamplifier combination with all equalization removed.[12] (This hypothetical case, based on a flat amplifier, illustrates how the different noise components contribute to dynamic range. In a practical reproducer, the reproducing preamplifier is not flat but falls at a 6 db per octave rate until 3180 cps, where it flattens out for the 50 microsecond post-emphasis. However, this equalization will affect both signal and noise in the same way, so that the signal-to-noise ratio will remain unchanged.)

It can be seen that in the high-frequency region, the head noise predominates and the signal-to-noise ratio is constant. As the mid-frequency region is approached, shot noise in the tube or transistor controls. This causes the signal-to-noise ratio to deteriorate at a 6 db per octave rate as the frequency decreases. At the low frequencies the $1/f$ noise of the amplifier takes over. It increases at a 3 db per octave rate which results in a signal-to-noise degradation of 9 db per octave.

In all of the other curves presented in this paper, we have used a new form of reproducing preamplifier developed by Erling Skov.[12] It completely eliminates the active first stage as a noise source. Thus, it eliminates the effect of shot noise and $1/f$ noise; the only noise remaining is that contributed by the head and the input transformer. An examination of Fig. 8 shows that the elimination of shot noise effects results in an improved signal-to-noise ratio in the mid- and low-frequency region.

[11] R. A. von Behren and R. J. Youngquist, "Frequency Modulation Noise in Magnetic Recording," *J. Audio Eng. Soc.* 3, 26 (1955).

[12] E. P. Skov, "Noise Limitations in Tape Reproducers," *J. Audio Eng. Soc.* 12, 280 (Oct., 1964).

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Mr. Langevin is a member of the Institute of Electrical and Electronics Engineers and a charter member of the Audio Engineering Society.