Reducing Distortion in Analog Tape Recorders

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A predistortion system is described which reduces the harmonic and intermodulation distortion of an analog tape recorder by a factor of 10. The system consists of an inexpensive analog computer coupled to a recording head which uses cross-field bias. The system is both accurate and easy to adjust. The cross-field bias, by narrowing the width of the critical region, ensures that low distortion is maintained through the entire audio band. Since the correction is applied to the recorded flux, tapes can be played with low distortion on any machine.

The system has been tested extensively by recording live classical music, and no audible artifacts have been found. Tapes made with the system are clearer and easier to listen to than tapes made on conventional machines.

INTRODUCTION: All analog magnetic recordings suffer from harmonic and intermodulation distortion, especially when material is recorded at high level. This distortion is primarily the result of saturation in the magnetic tape. It is well known that under some conditions the harmonic distortion can be reduced by properly predistorting the recording current, and several commercially made tape recorders have some nonlinear circuit in the recording amplifier for this purpose. Not all recording engineers find these circuits desirable, since simple predistortion systems (linearizers) have several drawbacks when they are used to record music. Unless the recording amplifier produces the exact inverse of the saturation nonlinearity of the tape, increased amounts of high-order distortion will result. Furthermore, the amplitude and phase of the distortion produced by a conventionally biased recording head is a strong function of frequency. Unless some method is used to compensate for this frequency dependence, predistortion will seriously degrade the distortion of the machine above 2 kHz at 15 in/s (380 mm/s).

The work described in this paper was guided by a simple principle: predistortion is not desirable unless its use with any input results in both lower amplitude and a lower order of distortion than the use of a conventional system. As a result of this work a predistortion system which is capable of reducing tape distortion by a factor of 10 was built.

The major problems with simple linearizers are the following.:

1) It is difficult to make an inexpensive recording amplifier which has the exact inverse of the nonlinearity of the tape.

2) Phase shifts in the ac biased recording process cause the predistortion to increase the distortion of the machine if the recording signal is above 2 kHz at 15 in/s (380 mm/s) or 1 kHz at 7.5 in/s (190 mm/s).

3) The overload properties of the recorder are degraded. Accidental overloads cause hard clipping and a very harsh sound.

4) The most inexpensive circuits are difficult to temperature compensate, which makes frequent adjustments necessary.

5) The most effective circuits are difficult to adjust for different types of tapes.

6) Unless the output of the nonlinear circuit is dc coupled to the head, the predistortion is not very effective on any asymmetric signal.

DISTORTION MEASUREMENTS

The exact nonlinearity of the tape was determined by measuring harmonic distortion as a function of tape flux level. These measurements were made on a studio tape recorder with variable bias current. The recorder electronics had very low harmonic distortion. The tape flux level was measured with an averaging voltmeter connected to the output of the playback preamplifier. All levels in this paper are thus total nonfiltered tape flux levels, relative to a fluxivity of 185 nWb/m (the "Ampex operating level"), in decibels. This fluxivity usually corresponds to a deflection of 0 dB on the volume indicator.

Harmonic distortion in a tape recorder is tricky to measure. There is enough wow and noise to make a notch-type fundamental canceling distortion meter unusable below about 1 % distortion at 500 Hz. When predistortion is used, there is also a rise in the modulation noise at the frequency of the third harmonic. A wave analyzer with a filter width of 12 Hz was used in these measurements. The filter width of 12 Hz was found to be wide enough to be independent of wow at most frequencies, and yet was narrow enough to exclude the modulation noise. Measurements of harmonic distortion with third-octave filters tend to be higher.

The results of third-harmonic measurements without predistortion for several different brands of tape are shown in Fig. 1. The major inaccuracy in these measurements occurs in determining the flux level of the recorded tone (± 0.3 dB). Cross-field bias was used [1]. (Cross-field bias will be explained in detail later in the paper.) Each tape was biased for minimum distortion at a flux level of 0 dB at 500 Hz. This criterion for biasing was chosen to simplify comparisons between these tapes. However, with cross-field bias the bias current which produces minimum distortion at 500 Hz severely alters the shape of the recording zone. The result is lower harmonic content when the tape is played, but very poor high-frequency response. For best operation of the predistorter the bias should be 1–2 dB less.

Harmonic distortion depends greatly on the design of the recording head. The first measurements used a metal two-channel Ampex recording head with a 25-μm gap length. The bias frequency was 200 kHz. This head produced about 0.6 % harmonic distortion at a flux level of 0 dB with Ampex 406 tape. A Philips ferrite head with a 12-μm gap length produced 0.3 % distortion under the same conditions. Adding cross-field bias reduced the distortion with both heads. The data shown in Fig. 1 were taken with the Philips head using cross-field bias, and they show 0.2 % distortion at a flux level of 0 dB. When biased for best operation of the predistorter, this head produced 0.3 % third harmonic distortion. The Ampex metal head also produced 0.3 % third harmonic distortion when biased for best performance of the predistorter, and the distortion did not improve when the bias was increased. This head is currently being used in this machine. (After only a hundred hours use the ferrite head shows ablation of the ferrite material at the edges of the gap. Further, at high frequencies the metal head produces a higher level without saturation.)

These measurements support other reports that ferrite recording heads produce lower distortion than metal heads, at least at low frequencies [2]. It is not obvious why this is so. The heads used in these experiments were different in permeability, gap length, gap spacer material, and high-frequency loss. The fact that both the metal head and the ferrite head produce similar distortion when used with cross-field bias might be an important clue. Further research should be done in this area, preferably by an organization with access to a great variety of heads. An improvement in the distortion properties of conventional tape machines might result.

The results of the distortion measurements are consistent with the results reported by Langevin [3]. They can be summarized as follows:

First, if the bias waveform is very good and the recording head is completely demagnetized, there is very little even-harmonic distortion. This is equivalent to saying that the tape transfer characteristic is completely symmetric.

Second, the amplitudes of harmonics higher than the third are very small.

Third, when plotted on a log–log scale such as Fig. 1, the third-harmonic distortion data can be fit by a straight line, at least over the most important part of its range. This is the fact which makes a good predistorter practical.

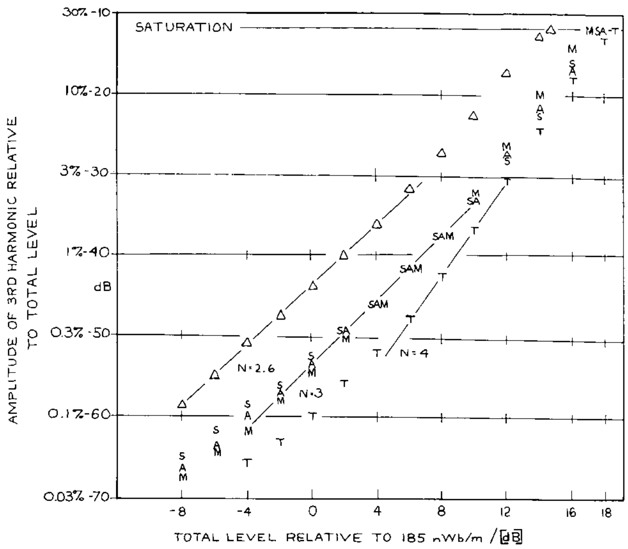

Fig. 1. Harmonic distortion as a function of tape flux level. No predistortion. Δ—Scotch 203 tape; S—Scotch 206 tape; A—Ampex 406 tape; M—Maxell UD 50 tape; T—TDK SD 150 tape. Philips ferrite recording head, cross-field bias, 15 in/s (380 mm/s), 500 Hz.

DEVELOPMENT OF THE PREDISTORTER

The shape of the curves in Fig. 1 suggest that the tape nonlinearity may be closely approximated by a power law.[1] Specifically, if ϕ is the flux recorded on the tape and i is the recording current,

$$\phi \propto \chi(i \pm C|i|^N)$$

$$- \text{ when } i > 0$$

$$+ \text{ when } i < 0.$$

The constant χ relates the recording field produced by the recording current to the recorded flux at low levels. $N - 1$ is given by the slope of the distortion data in Fig. 1, and N varies from 2.5 to 4 in the tapes tested. The constant C is best found by trial and error on a given recorder. However, it can be computed from the data in Figure 1. The value comes out to be about 0.05 for Scotch 202 if i is normalized to 1 at a flux level of 0 dB.

Guided by the above measurements, several circuits were constructed using analog computer techniques to produce the exact inverse of Eq. (1). After a long and sometimes frustrating development, the type of circuit shown in Fig. 2 was chosen. The majority of the circuit is designed to compute a power of the signal at its input. This part of the circuit is then placed inside the feedback loop of the recording amplifier to generate the exact inverse of Eq. (1). The first step in finding the power is to find the absolute value of the signal using an active rectifier. The next step takes the logarithm of this absolute value. An amplifier then multiplies the logarithm by the value selected for N. The antilog is then taken, giving the absolute value of the input signal raised to

[1] Eq. (1) is only valid for low values of i. As tape approaches saturation, the recorded flux approaches a constant value, whereas Eq. (1) predicts a continuous decrease. In the predistorter design a soft clipper, along with some feedback around the power circuit, partially correct for this error. There is not enough bandwidth in the recording process, and tape is not uniform enough from reel to reel to correct the distortion at high levels perfectly. It is better to design the predistorter to produce as few high-order harmonics as possible, and record at slightly lower level. For a very interesting discussion of the interaction between bandwidth, disc predistortion, and level, see [4].

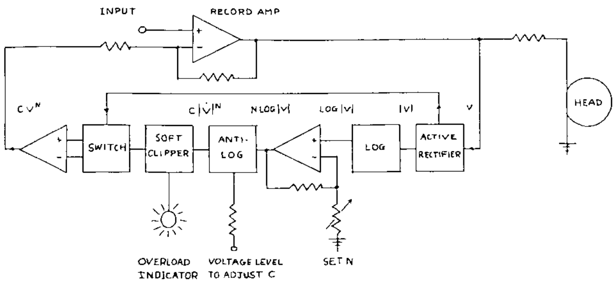

Fig. 2. Block diagram of predistorter.

the Nth power. This signal is soft clipped if necessary, and the sign is reinserted with an electronic switch. Timing errors in the switch do not produce crossover distortion, since the switching takes place only when the correction signal and its first two derivatives are zero (Fig. 3).

This circuit has many advantages. The constant C can be adjusted by means of a dc voltage, which means that several of these circuits may be ganged to one control. Thus a multichannel recorder may be easily adjusted for different tapes or bias levels. The exponent N is set by a single resistor, the value of which can be computed from the data in Fig. 1. The value of N need not be changed for most of the tapes in common professional use (N = 3). The circuit is inherently symmetric; both the positive and the negative parts of the signal are affected identically. The circuit is completely temperature independent, stable, and dc coupled. Parts for the circuit cost about \$8.00 in small quantities.

Fig. 4 shows the performance of this circuit using Maxell UD-50. At flux levels below +8 dB the distortion is almost completely removed. These measurements were made by setting the predistorter for minimum distortion at a flux level of +8 dB at 500 Hz. The distortion does not remain quite as low at other frequencies, but at low frequencies it stays below 0.1 % for any flux level below +4 dB. Notice that at the higher levels the error bars on the distortion-reduced data are rather large. This unevenness in the distortion is due to the lack of uniformity in the coating of the tape. About once a revolution of the supply reel there is a quick jump in the distortion. The size of the jump shown in Fig. 4 is about average for many brands of tape, although some individual reels may be perfectly uniform. Such a jump in distortion is usually accompanied by a slight drop in the tape output, and this drop can sometimes be heard if a noise reduction system is in use.

Even with these faults the improvement in harmonic distortion is dramatic and immediately noticeable by ear when pure tones are played. The decrease in intermodulation distortion when two randomly selected tones are recorded at the same time is even more dramatic.

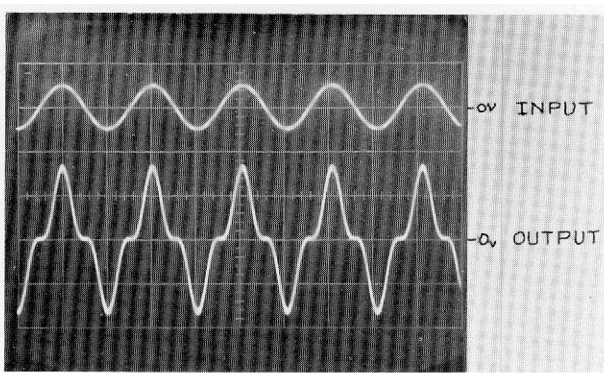

Fig. 3. Performance of circuit that raises input voltage to Nth power (N +3).

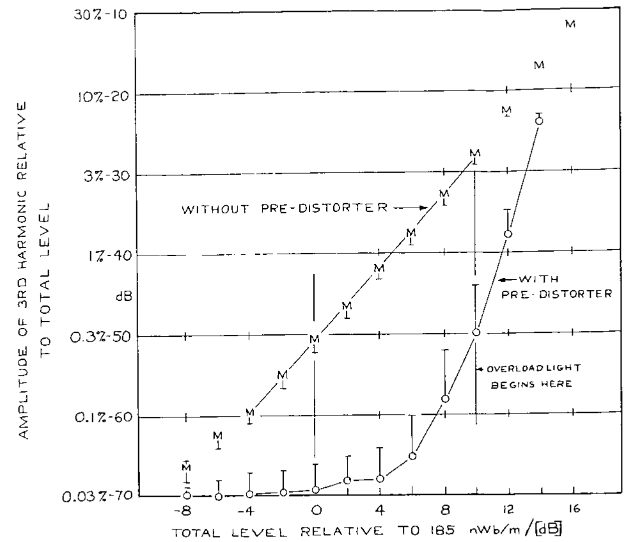

Fig. 4. Harmonic distortion as a function of tape flux level with and without predistortion. Ampex metal recording head, cross-field bias, 15 in/s (380 mm/s), 500 Hz, Maxell UD 50 tape.

The soft clipper in Fig. 2 limits the action of the predistorter whenever the instantaneous level exceeds +10 dB with Scotch 206. Above this level the distortion gradually rises to that of uncompensated tape. A red light is illuminated whenever a transient exceeds this level, and this light is a very valuable indication to the recording engineer. This limiting system was chosen after many listening tests and works well. Although the predistorter causes the higher order harmonic content of a grossly over-recorded tape to be somewhat greater than a normal tape at the same level, accidental overloads do not result in disaster.

We are accustomed to thinking that we can always pass an audio signal through a large capacitor without changing the signal in any audible way. However, the predistorter and the recording head are part of a very nonlinear system, and they cannot be decoupled in the usual way. If an asymmetric signal is being recorded (a series of short positive pulses would be a good example), a net current must flow through the head, or the predistortion will be less effective. Experiments indicate that most solo instruments (especially the human voice) produce asymmetric signals [3]. An ac coupled predistortion system is a good example of an audio device that can produce good results when tested with a single pure tone, but fails to work with music. The best test signal for this effect is a mixture of two oscillators with equal amplitudes tuned almost exactly in octaves. The odd harmonics of these two frequencies will not be completely canceled if ac coupling is used, and some even harmonics will be generated (Fig. 5).

The fact that the head is dc coupled causes no problems. Since the power-law circuit has no output at very low level, the dc offset voltage which appears at the recording head is determined only by the input offset voltage of the recording amplifier. Even without adjustment this offset is only a few millivolts, and the flux produced is less than that caused by the typical head magnetization.

For best results with the predistorter, the bias current should be very stable. Since the bias is set near the point of minimum distortion, drifts in the bias current do not affect the predistorter strongly, but the current should be held to within 3 %. There are enough variations from batch to batch in most tapes to make it necessary to readjust the predistorter whenever a new batch is started. Changing the tape speed also requires a small adjustment of the predistortion. Fortunately, only the constant C need be changed. This can be done by ear using a very simple test set. The set consists of a 400-Hz low-distortion oscillator and an RC notch filter tuned to 400 Hz. By simply varying the constant C while

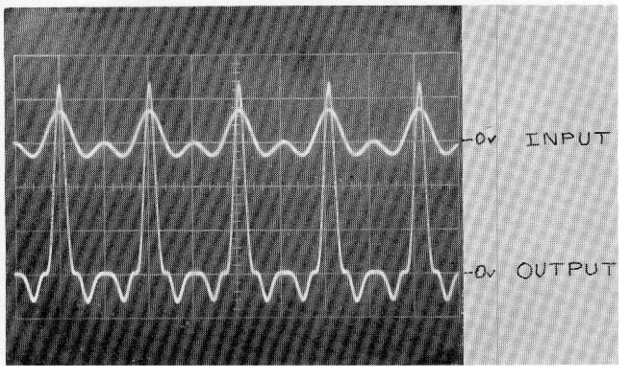

Fig. 5. Response of predistorter to asymmetric signal. The input consists of 1000 Hz and 500 Hz mixed equally. Notice that although the input has no dc component, the output appears to have a strong dc component. The measured dc component is + 0.5 major division.

listening to the playback of the oscillator through the filter, the third harmonic can be easily nulled to less than 0.1 %. Changing the control for C has no effect on the output level of the machine except at very high levels.

FREQUENCY-DEPENDENT EFFECTS

As was previously mentioned, the behavior of the predistorter with frequency is complicated. At low frequencies there are small shifts in the amplitudes of the distortion products which limit the effectiveness of the correction. However, once the predistortion has been set for the type of tape used and the tape speed, overall distortions of less than 0.1 % can be achieved at a flux level of 0 dB.

Unfortunately, at high frequencies the situation is not so simple. The major difficulty is with phase and amplitude shifts in the recording process as the wavelength becomes short. The linearizer assumes that the amount of harmonic distortion in the tape is independent of frequency, and that the fundamental, the harmonics generated by tape saturation, and the inverse of these harmonics generated by the linearizer are recorded in the same physical location on the tape. Most of these assumptions are incorrect.

These phase and amplitude shifts are serious. Unless some method of correcting them is found, a linearizer adjusted to work well at low frequencies will cease helping the distortion at all around 2 kHz at 15 in/s (380 mm/s), and 1 kHz at 7.5 in/s (190 mm/s). Above these frequencies the distortion with a linearizer becomes rapidly worse than the distortion in an uncompensated recording.

In an effort to understand this problem better, a network was placed in the output of the linearizer which could vary the phase and the amplitude of the third harmonics generated. The phase and amplitude shift necessary to eliminate the third-harmonic distortion generated by the tape at high frequencies was then measured. Throughout these tests the predistorter remained adjusted for best results at low frequencies. The results of these tests are shown in Fig. 6.

What is the meaning of these measurements? Consider the model for the recording process developed by Camras [1]. In this model the magnitude of the bias field determines the location on the tape where recording takes place. It can be shown that recording takes place in a "critical zone" on the trailing edge of the recording head, where the bias field falls from a value that is sufficient to saturate the coating to a value which has little effect (Fig. 7). The length of this region depends on the thickness of the coating and the sharpness of the hysteresis curve for the oxide. For a full discussion of this model, see [1].

When both the wavelength of the tone being recorded and the

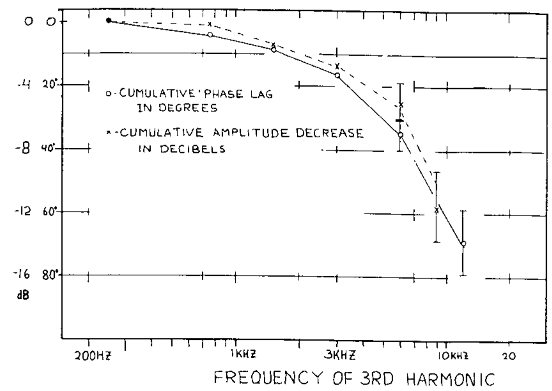

Fig. 6. Phase and amplitude of correction signal as a function of frequency if low distortion is to maintained at high frequencies and conventional bias is used. Scotch 202 tape, 7.5 in/s (380 mm/s), Philips ferrite recording head, conventional bias.

wavelength of its third harmonic are large compared to the length of this critical region, the predistorter can be expected to work well. However, as the wavelength of the third harmonic becomes comparable in size to the critical region, the situation becomes very complicated. Keep in mind that we are trying to cancel harmonics generated in the tape by recording over them with their exact inverses generated by the predistorter. If we assume that the harmonics generated by the tape nonlinearity are distributed uniformly through the critical region (i.e., that they accompany the fundamental), the phase data of Fig. 6 imply that the harmonics generated by the predistorter are recorded toward the trailing edge of the critical region. Thus they must be slightly delayed by a network if they are to still cancel the harmonics generated by the tape.

However, Fig. 6 also shows an amplitude effect. Apparently the harmonics generated by the tape must partially cancel each other when their wavelengths become short compared with the critical region. Unless the amplitude of the harmonics created by the predistorter are reduced, more distortion will be recorded on the tape than was there originally. This is the major reason that the performance of a simple linearizer is so poor at high frequencies.

Designing a network which would compensate for both the amplitude and phase shifts at the same time turned out to be very difficult. We had some success at 15 in/s (380 mm/s), through use of a delay line. However, two serious problems became apparent immediately. First, such a network is very dependent on the tape characteristics. A small change in the tape orientation or oxide thickness renders the network useless. Second, a network which successfully cancels harmonic distortion may cause an increase in intermodulation distortion when two high-frequency tones are recorded at high level. The low-frequency intermodulation products from two such tones may be increased by the action of the linearizer.[2]

It is remotely possible that these problems could be reduced by very careful design of a conventional record head. However, experiments with different heads were not encouraging. Many give shifts similar to the Philips head, and the Ampex alloy head has shifts about 1.5 times worse. The best solution is to use cross-field bias.

[2] An exact analysis of these phase and amplitude effects should include the fact that at high frequencies the playback head can only sense the flux near the surface of the tape coating. We have chosen not to consider the playback process in this paper because tests showed that a tape which played with low distortion on one machine played with equally low distortion on all machines. Tape predistortion is very different from disc predistortion in this respect. In disc predistortion the playback stylus radius, dynamic mass, and tracking angle are all very important to the success of the predistortion, and yet are not under the control of the recording engineer [4].

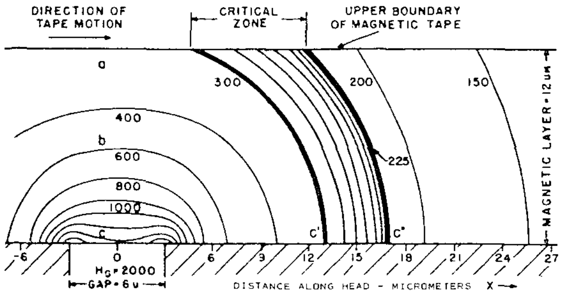

Fig. 7. Critical zone in tape at recording gap (from Camras [1]).

CROSS-FIELD BIAS

Cross-field bias can be explained using the model by Camras [1]. In the cross-field process a separate bias field is generated perpendicular to the recording head. This extra field adds to the bias field generated by the recording head in such a way as to cause a very sharp field gradient at the trailing edge of the recording gap. As a result, the critical zone is much narrower with cross-field bias than with conventional bias, and much better recording resolution results (Fig. 8).

Camras has developed a recording head which can produce cross-field bias in a single-sided head. Since such heads are not available, we used a bias head on the other side of the tape to produce the perpendicular bias field. The bias head (obtained from Tandberg of America) consists of an erase head with a relatively long (approximately 0.25 mm) single gap. It is mounted so that the gap of the bias head is about 0.5 mm upstream and 0.25 mm above the recording head gap. The actual spacings are not critical. It is only important that the bias head be located upstream of the recording head, and that there be enough room between them for the tape to pass freely. However, once set, these distances must be accurately maintained. Only the bias head is driven with bias current. The recording head is connected directly to the recording amplifier. The bias field in the recording head is supplied by induction. The bias current is set by adjusting the bias and the predistorter simultaneously for the best null of the third harmonic of a convenient frequency, such as the 400-Hz signal supplied by the test set, used at a tape speed of 7.5 in/s (190 mm/s). This value of bias current is also optimum for the high-frequency response of the machine, and produces a minimum of modulation noise [6]. Bias seldom needs adjustment.

The results of using cross-field bias were very gratifying. At 7.5 in/s (190 mm/s) the recorder would record up to 4 kHz without increasing the distortion above the values for uncompensated tape. This represents a fourfold improvement. At 15 in/s (380 mm/s) the performance was even better (Fig. 9).

Cross-field bias has several other advantages. It is possible to record a much higher level at high frequencies without saturation.

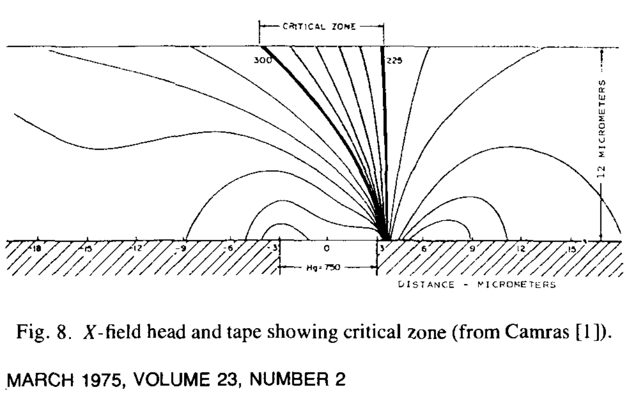

Fig. 8. X-field head and tape showing critical zone (from Camras [1]).

At 7.5 in/s (190 mm/s) and 15 kHz the level at which the tape begins to saturate is only 0.8 dB less than the maximum level that can be obtained without any bias. This corresponds to a recorded level of about -1 dB at 7.5 in/s (190 mm/s), with NAB equalization, the Ampex metal alloy head, and Ampex 406 tape. This is at least a 6-dB improvement over conventional bias. Perhaps the biggest added advantage of cross-field bias in a mastering recorder is that you can change tape types with little or no change in the recording equalization. Frequency response variations at 15 in/s (380 mm/s) are less than 0.5 dB even on tapes as different as Ampex 406 and Maxell UD 50. Thus tapes may be chosen with respect to modulation noise or dropout without needing to reequalize the machine.

LISTENING TESTS

Experimental use of the predistortion system for recording classical music has been rewarding. The sound is very pleasant and easy to listen to for long periods of time. The most obvious subjective impression is the clarity of the sound. Organ music is dramatically improved by the reduction in intermodulation distortion, but even on very complex material some improvement is noticeable. On music with massed strings or voices the predistortion gives improved smoothness, less scratch, and, surprisingly, less apparent modulation noise.

As usual, there is a price to pay for such improved sound. All predistortion systems, either for tape or disc, must be both correctly adjusted and very carefully used. This predistortion system obeys the principle stated at the beginning of the paper, only at moderate levels. If users of predistortion increase their average level, it is very likely that the quality of their tapes (or discs) will be lower than if no predistortion were used. If the level is raised above normal levels the high-frequency distortion (which is only partly reduced by the predistorter) may become noticeable [4]. More importantly, an increase in average level causes overload to occur much more frequently [5], and the action of the predistorter will make these overloads more serious. Higher order harmonics will begin to be apparent in some types of music, and many listeners will object to the sound. If reducing distortion is your object, you must give up the notion that a very high level is synonymous with quality.

When the predistorter is installed in a recorder which has a standard volume indicator (vu meter), the overload light can be used to indicate the proper level. On continuous material, such as organ or a capella chorus, an infrequent flicker indicates the perfect level. The level must be kept low enough to keep the light from flashing brightly. The sudden onset of distortion is very

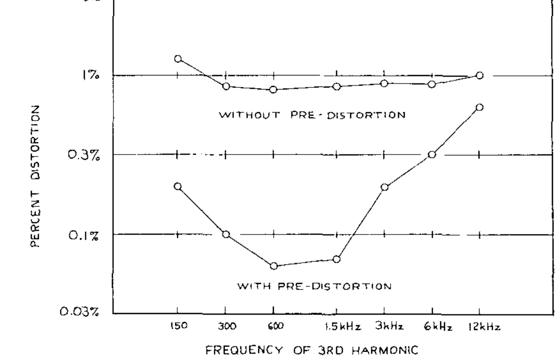

Fig. 9. Distortion as a function of frequency. Ampex 406 tape, 4-dB level, 15 in/s (380 mm/s), Ampex metal head, cross-field bias, NAB equalization.

disturbing in such music, especially when one has become accustomed to its absence. With material which contains many transients, such as any music with drums, the light may flash rather merrily without any easily audible effect. Saturation of the tape should be avoided with all material. It is seldom possible to record a high-quality tape with the volume indicators indicating more than +2 dB (Ampex 406 or Scotch 206 tape). If the recorder is equipped with peak program meters, the maximum level should be a fluxivity of 700 nWb/m.

These recording levels are based on experience and personal preference. The author believes that recorded music is much more pleasant to hear when it contains no audible distortion. To our ears, normal recording levels (in conjunction with Dolby A noise reduction) provide an ample signal-to-noise ratio. Other people have used the predistortion system to record very high levels without evident discomfort.

The predistorter has turned out to be very useful in the study of the audibility of different types of distortion. Not only does it supply high-quality tapes for use as source material, it can be wired to produce an electrical replica of the distortion which would be produced in a conventional tape recorder. Listening to this signal is most unpleasant and can serve as an excellent ear training for hearing tape distortion. This signal can also be used to determine at what level distortion from a conventional tape recorder becomes audible. Naturally, this threshold of audibility depends very much on the type of music used, but it can be below 1%.

CONCLUSIONS

With good music and good miking, tape recordings made with the predistorter can be stunning. The only defects which remain are the tape-related problems of modulation noise, coating irregularity, dropout, and skew.

Requests for further information on this predistortion system are welcomed by the author and may be addressed to him at 15 Bellevue Avenue, Cambridge, Mass. Manufacturing rights are available. If there is sufficient demand from individuals interested in experimenting with distortion reduction, it might be possible to produce a few of the nonlinear circuits as modules.

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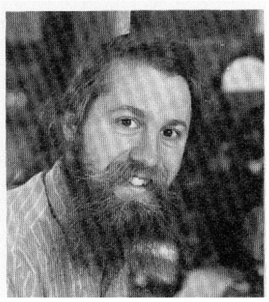

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