Distortion in Tape Recording

Common sense, careful thinking, and a set of accurate measurements will enable anyone to choose an operating point which will give the best over-all quality from his tape recorder. The author tells you how.

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More and more audio fans, especially in areas having one or more "good music" FM stations, are making off-the-air tape recordings. Often the program source is live—symphony, chamber music, instrumentalist, singer, or choral group—while at other times the source consists of a first rate disc or tape recording. In either case, many owners of tape recorders have numerous opportunities to capture musical moments worth preserving, either indefinitely or until a better rendition comes along. Moreover, some recordists make tapes of their own singing or instrumental playing, which they are eager to hear for pleasure or improvement.

Unfortunately, the recording does not always sound "clean" in playback. It may lack the effortless, silky quality of the original source. Due to distortion, it may have a more or less grating quality, either constantly or only during loud passages. This situation is not confined to amateur recordings. Sometimes professional recordings contain objectionable distortion.

Distortion, presuming none in the source, may be due either to a fault in the tape recorder or to an excessive amount of signal applied to the tape. The latter is of concern here, that is, distortion resulting from high signal levels, and it shall be assumed that the tape recorder heads and electronics (amplifiers and bias oscillator) are in proper condition.

Although in a direct sense over-recording—that is, the desire for a high signal to noise ratio—may be blamed for distortion, in a basic sense the desire for wide frequency range, perhaps unnecessarily wide, may also be partly at fault. This can be true in two ways. First, in order to maintain good response out to 15,000 cps or so at a speed as low as 7.5 ips, the amount of high-frequency preemphasis required in recording may be sufficient to cause tape overload at treble frequencies. Above 7,500 cps, where most of the boost occurs, there would be virtually no audible harmonic distortion inasmuch as the harmonics fall outside most persons' hearing range as well as outside the recorder's pass band, which cuts off sharply beyond 15,000 cps or earlier. However, in any nonlinear system there would still be intermodulation products generated by interaction between two high frequencies or between a low and a high frequency; many of these products would be within range of the ear and the recorder.

The desire for extended high-frequency response can also be responsible for distortion by virtue of the required bias setting. Over the bias range customarily used, an increase in bias generally causes distortion to fall, while a decrease in bias generally causes distortion to rise. However, increased bias also results in greater attenuation of high-frequency response. The desire to maintain high-frequency response well beyond 10,000 cps at low tape speed may lead to bias reduction, thereby resulting in greater distortion at a given recording level.

The following discussion seeks to throw light on:

1. The relative changes in harmonic and intermodulation distortion as input level is varied.
2. The relative changes in harmonic and intermodulation distortion as bias is varied; determination of bias for minimum distortion.
3. Variation among tapes with respect to intermodulation distortion.
4. Method of setting bias so as to yield the optimum combination of high signal-to-noise ratio, wide frequency range, and low distortion.

It should be made clear that the measurements described in the following discussion are not definitive in the sense of providing exact values under given recording conditions. Rather, they are broadly indicative of what happens. The values may fluctuate as the test is repeated at a different time, on a different machine, with a different tape, at different temperature or humidity, and so on. However, the tests have been repeated sufficiently to indicate reliably the general nature of the observed phenomena.

The measurements underlying the following discussion were made on two professional tape recorders in the $2,000 class, operating at 15 or 7.5 ips, and using a commercial high quality tape. The machines have separate record and playback heads, permitting immediate plotting of results. Test equipment consisted of an audio oscillator, an oscilloscope, a sensitive a.c. VTVM, a harmonic distortion tester which measures the total signal content after the fundamental has been filtered out, and an SMPTE type IM tester which, using 60 and 6,000 cps respectively in 4:1 ratio, measures the extent to which the high frequency is modulated by the low frequency.

Variation of Distortion With Input Level

Invariably, tape recorder specifications make no mention of IM distortion, referring only to harmonic distortion. Tape recorders have a VU meter or other type of recording level indicator to show when recording level is such as to produce 1 or 2 or 3 per cent harmonic distortion. However, as *Fig.* 1 reveals, when harmonic distortion is still at relatively innocuous levels, below 3 per cent or so, IM distortion can be disruptive—20 or 30 per cent or more.

The measurements in *Fig.* 1 were made on a machine operating at 15 ips with bias set approximately at optimum, in the manner described later. The 0 db reference input level for measuring IM distortion was equated to that for harmonic distortion by adjusting these input levels for equal peak-to-peak readings on an oscilloscope.

Figure 1 indicates that IM distortion begins to rise much earlier than harmonic distortion, and that the rate of increase is far greater for IM distortion. After IM distortion has reached about 4 or 5 per cent, it rises very precipitously. It may be observed, therefore, that in the effort to add a few db to signal-to-noise ratio, the recordist runs the risk of trading a slight decrease in noise for a large increase in IM distortion.

For the purposes of the measurements underlying this discussion, the recorder was adjusted so that its VU meter indicated 0 when IM distortion was approximately at the maximum level considered tolerable for high fidelity purposes, say about 2 or 3 per cent.

In actual use, however, the recorder should be adjusted so that the VU meter indicates 0 for a signal perhaps 8 or 10 db *below* that which causes maximum

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allowable distortion, because on transients the pointer of the VU meter may lag 8 db or more behind peak signal level. If in actual use, the meter were calibrated to read 0 for a steady-state signal which produces 2 or 3 per cent IM distortion, allowing the needle to hit 0 when recording program material would often bring the reading into the region of extreme distortion, albeit briefly. Therefore, it is necessary to allow a margin in adjusting the VU meter. Even so, unless the recordist uses discretion, based on the nature of the music he is recording, fortissimo portions of a musical work, or at least the attacks, can be marred by the breakup and fuzziness symptomatic of distortion, even though the VU meter indicates only 0.

The recordist is forced into a choice among three alternatives: (1) to accept occasional high distortion in exchange for an improved signal-to-noise ratio; (2) to make some sacrifice in signal-to-noise ratio (which means relatively more hum, tube noise, and tape hiss) in exchange for low distortion throughout the recording; (3) to ride gain, reducing input level during loud passages, which means exchanging dynamic range for low distortion throughout a recording. The last alternative implies ability and willingness to compare the program source against a score and accurately anticipate changes in level.

The recordist's decision on the course to follow will be influenced by the tape recorder he is using and purposes for which it is employed. If it is a quality machine with a high signal-to-noise ratio, he may well follow the expedient yet satisfactory course of setting recording level just low enough so that peak passages are recorded at a level of distortion which, at least for a brief period, has no appreciable effect upon the listener. On the other hand, if the machine's signal-to-noise ratio is inferior, the preferable course may be to accept some obvious distortion during peaks for the sake of keeping background noise comfortably low throughout the recording. The program source can also influence the decision. For example, a relatively high input level might be used to record the spoken voice because in this instance a considerable amount of distortion can usually go unnoticed. On the other hand, one might have to exercise considerable more restraint in setting gain for an organ or piano in order to obtain a pleasing similarity to the original.

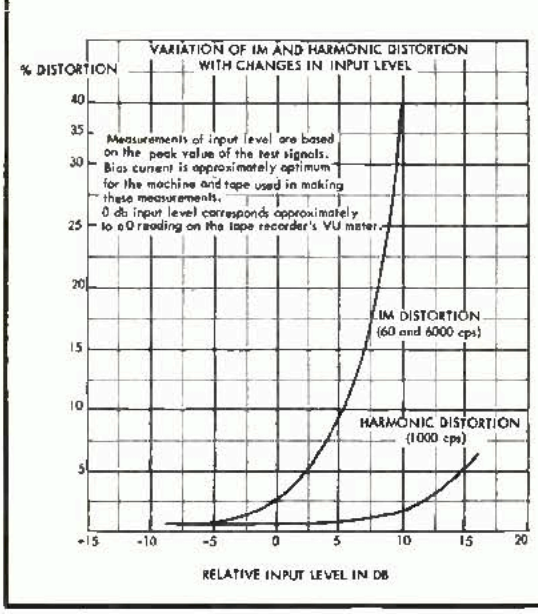
Variation of Distortion With Bias

Figure 2 indicates the effect of bias current on distortion, using two relatively high input levels. It must be taken into account that as bias varies so does the amount of signal recorded on the tape. In short, tape output as well as distortion varies with bias. However, we are only interested here in how distortion varies with bias. Therefore it is necessary to hold tape output constant. For this reason, the input level was constantly adjusted to maintain a fixed indication on the VU meter *in playback*. Curves 1 and 2 are based on a playback indication of 0 db on the VU meter. Curves 3 and 4 result from levels 3 db higher. At the 0 VU playback level, with bias set for minimum IM distortion, the harmonic distortion test signal was matched to the IM test signal by comparing peak-to-peak playback amplitudes on the oscilloscope.

Figure 2 reveals that: (1) IM distortion once again varies much more than harmonic distortion; (2) Distortion does not indefinitely continue to decline as bias is increased, but rises again, and this rise is sharper in the case of IM distortion; (3) The higher the input level, the more critical is the bias setting for minimum distortion; thus, in order to find the minimum-distortion bias with ease, it is merely necessary to use a very high input level. (4) A rise in input signal level produces the least increase in distortion when bias is set for minimum distortion.

From the above it can be concluded that to the extent the recordist seeks to maximize signal-to-noise ratio by turning up gain, the more important it becomes that he adjust bias properly for the particular tape he is using. Otherwise he may get much more distortion, especially IM, than is acceptable.

(An interesting phenomenon is displayed by the left portion of the curves in *Fig.* 2. If bias current is reduced enough below the normal working range, distortion drops again. Inasmuch as a reduction in bias current serves to improve high frequency response, it might seem that one might profitably operate in the area of extremely low bias current. However, there is good reason for not doing so. The reduction in distortion achieved by using very low bias current is most striking for high input levels. At low input levels, however, distortion re-



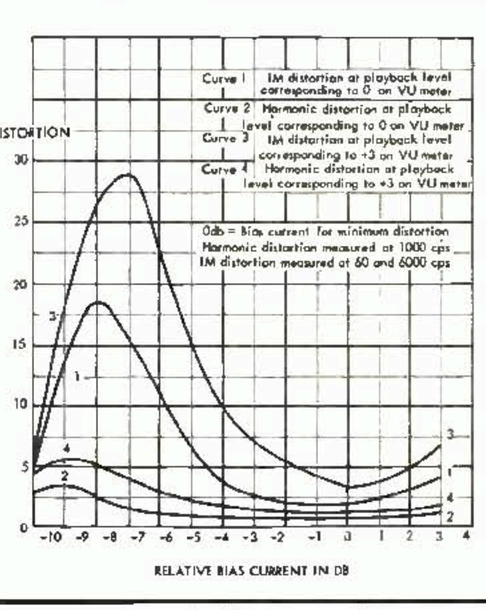


Fig. 1 (left). Variation of IM and harmonic distortion with changes in input level. Fig. 2 (right). Variation of IM and harmonic distortion with changes in bias current.

mains higher than when operating in the normal bias range. Furthermore, the amount of recorded signal drops at low bias values, so that to maintain the same amount of tape output requires considerably greater power from the output stage supplying the record head.)

Variation in Distortion Among Tapes

Using a relatively high recording signal, several popular brands of tape were compared with respect to IM distortion. Input level was varied so that each tape produced the same output level as read on the VU meter during playback. Bias was adjusted for each tape until minimum distortion was obtained. Following were the results.

Tape	Minimum IM Distortion	Relative Bias Setting
A (reference)	7.6%	0.00 db
B	9.0	.75
C	11.0	−.50
D	10.0	0.00
E	3.5	−1.00

It is interesting to note that the bias setting for minimum distortion varied only moderately from tape to tape, while the amount of distortion varied considerably more. However, these findings would not be sufficient on which to base the choice of a tape. It would be further necessary to consider the tape's frequency characteristics at the bias current resulting in minimum distortion, the *shape* of its output versus bias curves for different frequencies, its noise properties, and so on.

Determination of Optimum Bias Current

Let us assume that on the basis of curves such as in *Fig.* 2, the bias current for minimum distortion has been ascertained, using a given machine and a particular tape. However, depending upon the tape speed and upon the brand and kind of tape (regular, high output, long-play, etc.), high-frequency response may be inadequate at this bias current.

As previously stated, treble response goes down as bias is increased. This is a wavelength effect. Inasmuch as a given frequency results in a shorter wavelength at reduced tape speed, the problem of poor treble response due to high bias current is most serious at the lower speeds such as 7.5 and 3.75 ips. Consequently at these speeds, in order to maintain satisfactory response, it is probably necessary to use less bias than the amount permitting minimum distortion. This means greater distortion for a given amount of tape output, or less output for the same distortion (lower signal-to-noise ratio), or a compromise between the two.

Figure 3 indicates the procedure to be used in determining optimum bias current. It is assumed that the tape recorder provides ready means for varying bias current and for varying treble preemphasis in recording. It is further assumed that playback equalization is fixed (in accordance with the NARTB standard for 15 ips). Curves 1 and 2 in *Fig.* 3, representing variation of IM distortion with bias, have been redrawn from *Fig.* 2. 0 db bias represents bias current for least distortion.

When the tape recorder represented in *Fig.* 3 is operating at 15 ips, Curves 3 and 4 respectively show how response at 400 cps and at 15,000 cps varies with bias; input level was kept low enough to avoid any possibility of saturation. 400 cps is used as a reference frequency, not being affected by equalization used in the record preamplifier. When 0 db (minimum distortion) bias current is used, response at 15,000 cps is 1.5 db higher than at 400 cps. In order for frequency response to be perfectly flat at 15,000 cps, it is necessary either to increase the amount of bias current to 1.4 db or reduce the amount of treble preemphasis. Since a rise in bias current would increase distortion, the desirable step is to lower the treble boost.

Thus it can be seen that at a speed as high as 15 ips, at least for the machine and tape represented in *Fig.* 3, one can set bias for minimum distortion and yet maintain response out to 15,000 cps. (It should be noted that a final determination of the amount of treble preemphasis required would depend upon a frequency-response run. Possibly, if response at 15,000 cps is kept flat, there would be excessive boost at lower treble frequencies. Thus in order to achieve the flattest possible response over the treble range as a whole, it may be necessary to accept response which is a few db down at 15,000 cps.)

Now let us consider the situation where the tape recorder represented in *Fig.* 3 operates at 7.5 ips. Curve 5 shows the 15,000-cps response at 7.5 ips as bias is varied. At minimum distortion bias, 15,000 cps response is about 10 db below 400 cps. Possibly this situation can be improved by increasing the amount of treble boost in the record amplifier. On the other hand, increasing the treble boost may cause appreciably greater tape overload in the upper treble range. Let us therefore assume that Curve 5 is based on the maximum amount of treble boost which may be safely used, taking into account the typical distribution of musical energy over the frequency range;[1] any additional treble boost would increase the likelihood of distortion.

Consequently, in order to maintain response out to 15,000 cycles at 7.5 ips, it is necessary to reduce bias. Curves 3 and 5 intersect at approximately −3.6 db bias; at this reduced bias, flat response out to 15,000 cps can be had. However, as bias is reduced to −3.6 db, IM distortion rises from 3.5 to 8.5 per cent for the signal level represented by Curve 1. On the other hand, by sacrificing 3 db in signal-to-noise ratio—that is, reducing signal level to the proportions represented by Curve 2—IM distortion can be kept at only 3 per cent when bias is −3.6 db.

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[1] See the article by Herman Burstein, "Tape Recording Equalization," *Radio & Television News*, February 1956.

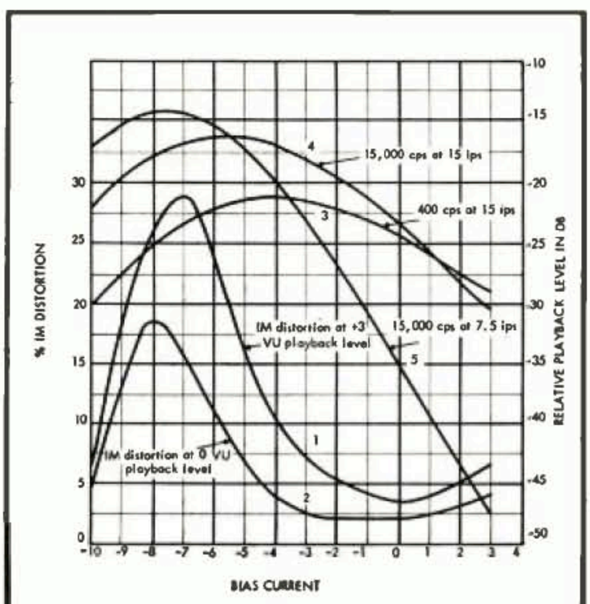

Fig. 3. Determination of optimum bias current.

TAPE DISTORTION

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It would seem that a reduction of only 3 db in signal-to-noise ratio is little enough to exchange for frequency response good to 15,000 instead of 7,500 cps. However, there are two counter views: (1) Few if any tape recorders have decibels to spare in the matter of signal-to-noise ratio. Whereas ratios of 70 db, 80 db, and better are commonly found in preamplifiers and power amplifiers, a tape recorder is doing extremely well if it gets up to 55 db. The designer of such a tape recorder fights hard for every last decibel or two in striving for a figure of 55 db, and a sacrifice of 3 db is consequently not unimportant. (2) Operating at –3.6 db bias puts the tape recording process into a region where a slight miscalculation as to input level produces a large difference in IM distortion. On the basis of *Fig.* 2 (or 3) at 0 db bias a 3 db miscalculation in level increases IM distortion only 1.5 per cent, but at –3.6 db bias the same miscalculation raises distortion by 5.5 per cent.

In view of the above two considerations, a recordist or tape machine designer equipped with the necessary test instruments might decide that at 7.5 ips he cannot afford, in terms of distortion and/or noise, the luxury of response more or less flat to 15,000 cps. Instead he may decide on a compromise course, shifting to a bias current intermediate between 0 and –3.6 db. Thus, for example, his choice might cost him only a 1 db reduction in signal-to-noise ratio and a reduction in flat response from 15,000 cps to 10,000 or 12,000 cps. At the same time he would have better protection against the consequences of overrecording than if he used –3.6 db bias.

In order to find this optimum bias point, it would be necessary to draw a number of curves similar to Curve 5 in Figure 3, showing the effect of bias current variations on several frequencies such as 9,000, 10,000, 12,000 cps, and so on. Input level should be kept 20 to 30 db below maximum recording level to avoid saturation. Then for each frequency curve one can evaluate, along the lines indicated in Fig. 3, what flat response out to this frequency signifies in terms of increase in distortion and/or reduction in signal-to-noise ratio because of departure from 0 db current. Based on these evaluations, the bias current can be selected which reflects the individual's concept of the optimum combination of frequency response, distortion, and signal-to-noise ratio within the capacities of a particular machine.

Conclusions

It has been pointed out that IM distortion can be a serious problem in tape recording, especially if one attempts to cut close to the line in maximizing signal-to-noise ratio; that adjustment of bias current can be quite critical if distortion is to be kept to a minimum at high recording levels; that departures from this critical bias point can exaggerate the consequences of excessive recording levels; and that, if the necessary test equipment is available, a definite procedure can be followed to determine first the bias current for minimum distortion and secondly the bias current which at speeds below 15 ips provides the most satisfactory compromise among the requirements of low distortion, wide frequency response, and high signal-to-noise ratio.

A number of judgments are required in determining maximum recording level and optimum bias current. How wide need frequency range be in order to give essentially satisfactory results? How much IM distortion is tolerable? How much for a split second? How much for a few seconds? How much for half an hour?

These of course are subjective judgments. Consequently the determination of maximum recording level and optimum bias current is not a hard and fast procedure.

The writers have heard a number of professional master tapes, one or two generations removed from the original, which, according to indications of a properly calibrated VU meter in playback, were recorded at excessively high levels; the VU pointer frequently kicked to full scale instead of staying below 0. Yet many of these seemingly over-recorded tapes nevertheless sounded clean to the ear. Although IM distortion was undoubtedly present in substantial degree, perhaps it was occurring in such short bursts as not to be disturbing; or perhaps the nature of the musical selection was such as to mask the effects of distortion. On the other hand, the writers have listened to master tapes seemingly recorded at conservative levels, yet less clean-sounding than desirable. Possibly other factors than recording level and bias setting intervened between the original source and good reproduction. At still other times the writers have listened to recordings velvety smooth except for a relatively high background of hum, noise, and tape hiss. They would gladly have accepted more distortion for less background distraction.

The above observations point up the

fact that top quality tape recording is both a technique and a craft. It is advisable to have a technical grasp which enables one to adjust a tape recorder, if feasible, so as to make the most of its capabilities with respect to distortion, frequency range, and signal-to-noise ratio. At the same time, one must have the craftsman's touch, which is based on experience, qualitative judgment, and—the best instrument of all in audio work—an acute ear.