Review of the Present Status of Magnetic Recording Theory

W. W. WETZEL*

PART III

In this series of three articles, Dr. Wetzel presents the first complete discussion of magnetic tape recording theory for engineers.

IN THE two foregoing parts we have examined some of the properties of magnetic materials and the forces to which the materials are subjected during recording. In Part III we shall summarize the effects and illustrate the results with data taken from actual measurements. We shall then examine noise and distortion phenomena from the experimental point of view since theories of the cause of noise and distortion are far from complete.

Summary

In order to compare the over-all response of a tape as a function of frequency it appears fair to examine the outputs at different frequencies on the basis of some form of constant input. The basis usually selected is that the maximum exciting field in the recording gap be made the same for each frequency, i. e., the total maximum flux be made equal before demagnetization. This is done by keeping the exciting current in the playing head the same for each recorded frequency. The output curves so obtained are known as constant current frequency-response curves and have been generally adopted as demonstrating one characteristic of a magnetic medium.

Forgetting for the moment demagnetization and the gap effect of the reproducing head, let us see what might be expected of constant current recording. If the field of the gap induced the same maximum remanent flux $\varnothing$ regardless of frequency, we should have as an expression of the flux:

$$\varnothing = ai \sin \omega t$$

On playback where the derivative of the induction is proportional to the response, we have for the output voltage "V" of the reproducing head

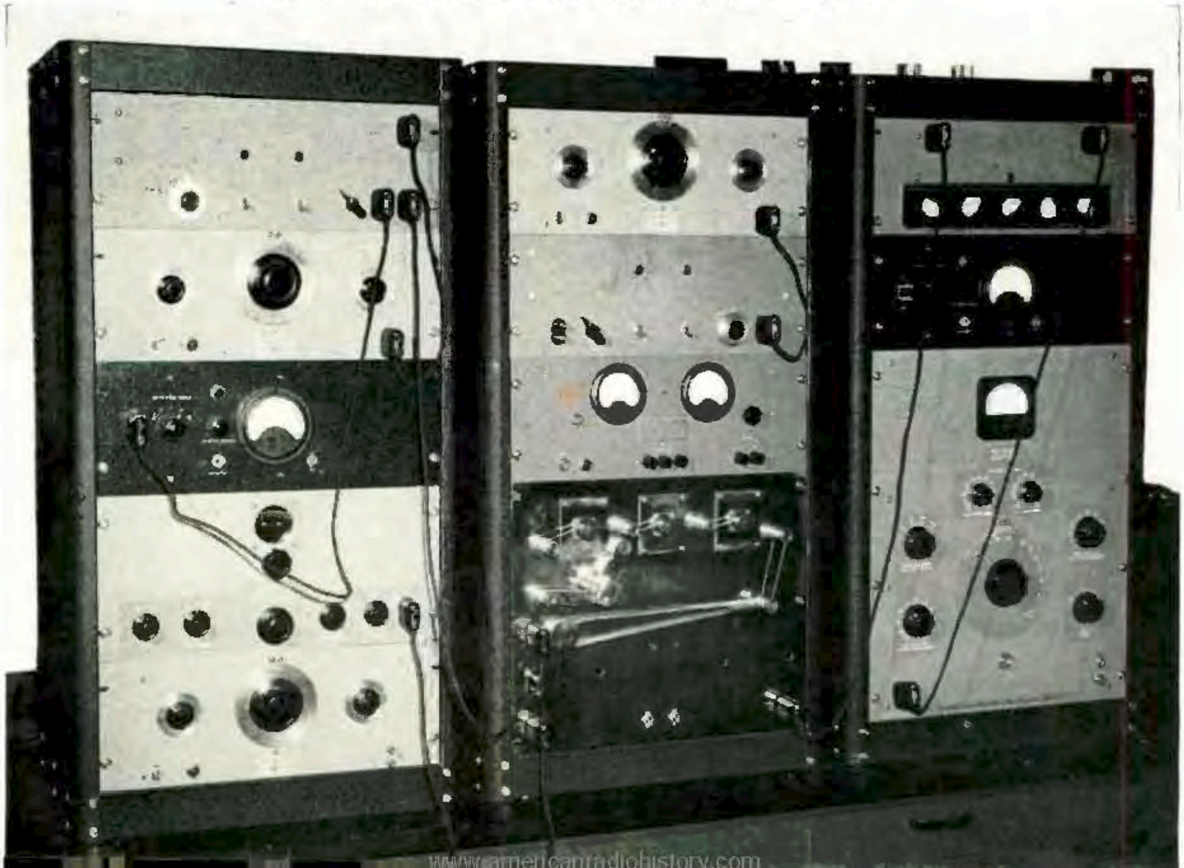
$$V = b\frac{d\varnothing}{dt} = abi\,\omega \cos \omega t$$

Since the maximum output voltage "V" is directly proportional to $\omega = 2\pi f$, we see that the output may be expected to vary linearly with the frequency. This represents an output which increases 6 db per octave and is illustrated by the straight *Curve 1*, *Fig. 1*.

If to the above considerations we add the effects of demagnetization on the induction remaining in the tape, we obtain *Curve 2*, which indicates that a large drop in remanent induction accompanies increased frequency.

Superimposing on the above effect the gap effect of the reproducing head we

Fig. 2. Equipment assembly for testing loops of magnetic recording tape.



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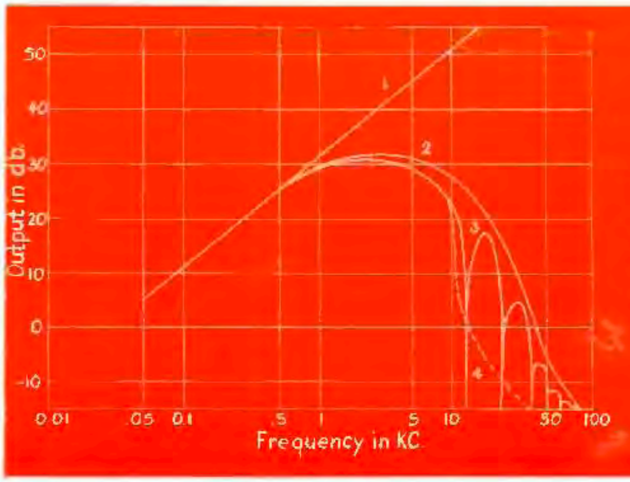
*Minnesota Mining and Manufacturing Co., 900 Fauquier Ave., St. Paul, Minn.



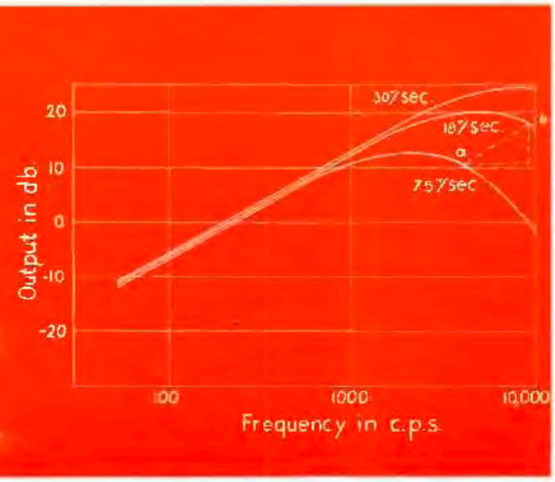


Fig. 1 (left). Showing Curve 1, the 6 db/octave increase inherent in constant current recording; Curve 2, the effect on Curve 1 of the demagnetizing forces; and Curve 3, the addition of the characteristics of the reproducing head. Curve 4 is added to illustrate the desirability of an amplifier cut-off at high frequencies. **Fig. 3 (right).** Showing the effect on the frequency response characteristic obtained by changing the speed of the tape drive. American tape.

obtain *Curve 3* which shows the over-all frequency response of the magnetic recording system dissociated from amplifier characteristics.[1]

The chief contributors to *Curve 3* are the remanent flux pattern on the tape and the geometry and permeability of the reproducing head. For purposes of illustration it has been tacitly assumed that the tape and its flux pattern were driven at some constant velocity across the reproducing head. This permits the plotting of the output against frequency "*f*" although the wavelength "*l*" is the basic constant upon which the flux pattern depends.[2]

We are now in a position to predict the effect on the frequency response curve of using the same recording and reproducing system at a different velocity of tape drive. For constant current recording the flux on the tape will be identical, wavelength for wavelength, independent of the velocity.

Because the output of the reproducing head is proportional to the rate of change flux, if the velocity is halved the output is reduced 6 db. If the velocity is halved, any given wavelength corresponds to half the frequency. The effect of a velocity change would be that of moving *Curves 2* and *3* along *Curve 1* until any reference point on the curves corresponding to a given wavelength for the initial velocity reaches the frequency corresponding to the new velocity.

The effect of changing the gap width of the reproducing head is more complex and will not be discussed here beyond the mention that the effective gap is not equal to the physical gap width.

The Loop Tester

Because it offers the convenience of being able to study a small sample of wire or tape for any given length of time, most laboratories engaged in the study of recording materials employ loop testers. On this device a loop of tape or wire is driven continuously and repeatedly over erase, record and playback heads. An example of a loop tester with the associated instruments is shown in *Fig. 2*. Separate variable oscillators and amplifiers are provided for the bias

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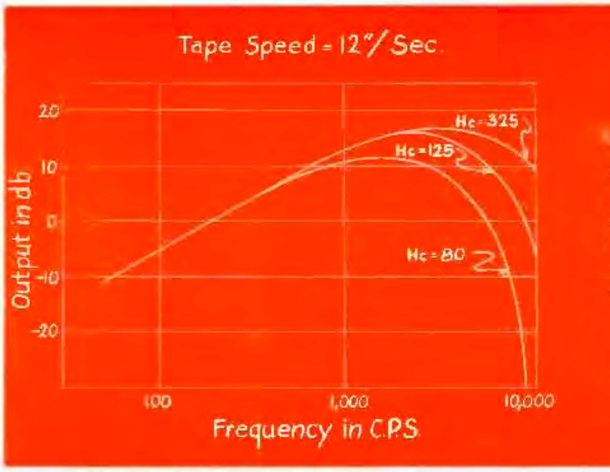
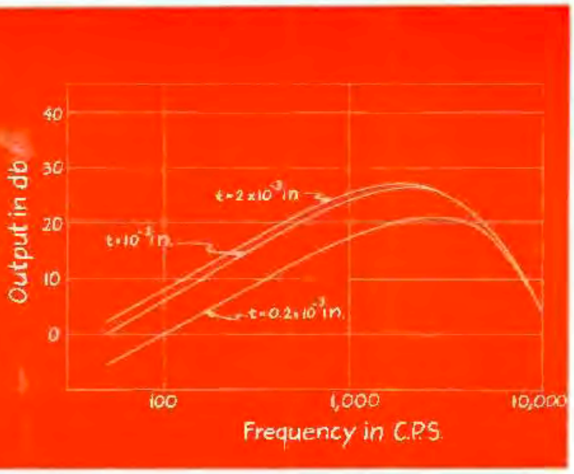
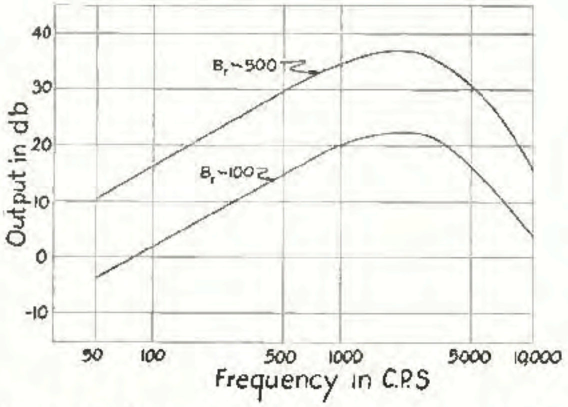
[1] It is advantageous from two considerations that the amplifiers cut off as abruptly as possible at frequencies above those which we intend to record. This sharp upper cut-off is illustrated by the dashed *Curve 4, Fig. 1*. This cut-off has these beneficial effects: *a*) it reduces the background noise to the extent of reducing the contributions in the upper frequency range, and *b*) it represses harmonic distortion to the extent that harmonics above cut-off frequency will be suppressed.

[2] The equation for the velocity "v" is obviously $v = fl$.

Fig. 4 (left). The frequency response is shown to vary with the coercive force of the coating material in a manner similar to that obtained by a velocity change. Experimental tapes. **Fig. 5 (right).** Illustrating the law of diminishing returns applied to coating thickness on a tape. Experimental tapes.







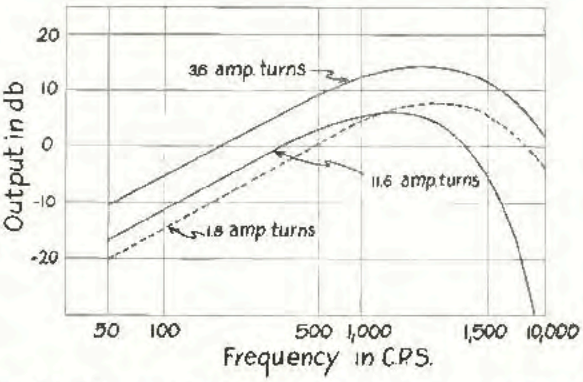


Fig. 6 (left). Showing the effect of varying the remanence of a coating material. Experimental tapes. Fig. 7 (right). Showing the influence on output of varying the bias current. Note the decrease in output at high frequencies obtained from an excessively high bias. American tape.

and erase supplies. The audio signal or signals are obtained from audio frequency oscillators which have sufficient output to supply the recording current without additional amplification.

The output of the playback head is amplified and examined in an oscilloscope, on a Ballantine voltmeter or the wave analyzer. A low pass filter cutting off at 16 kc is incorporated in the output amplifier to eliminate the pick-up of bias and wipe frequencies. Similarly, high pass filters suppress the power line frequencies in the bias and wipe amplifiers.

This combination of instruments permits one to make many of the determinations required to evaluate tapes. The graphs illustrating the remaining portion of this article were assembled from measurements taken on this equipment. The plots are generalized and occasionally represent smoothed readings. The omission of reference voltages and specifications of the heads is intended to indicate the generalization.

Miscellaneous Observations

In the discussion of the general theory we have made certain predictions concerning the effects of variables on the output characteristics. We shall illustrate a number of these effects by considering the results obtained on the loop tester.

The effect of increasing the velocity of the tape drive was shown to be the shifting of each point on the frequency response curves along a 6 db octave line. The curves shown in *Fig. 3* give the results obtained on an American tape by varying the speed holding all other factors constant. The triangle illustrates the construction proposed by Holmes[3] for calculating the response for any velocity if it is known for one velocity. Point *a* on the 7.5"/sec. curve transferred to point *b* on the 18"/sec. curve along the hypotenuse of a triangle sloping at 6 db/octave whose base is the log $\frac{I_2}{I_1}$ or log $\frac{v_2}{v_1}$.

Fig. 4 shows the frequency response as a function of H_c alone. Since it is difficult to obtain materials of the same remanence but widely different values of the coercive force, the curves were "normalized" by shifting them vertically until the response at the lower frequencies coincided. It will be observed that the increase in velocity has essentially the same effect as an increase in H_c. Other factors being equal, the high coercive force tapes may be used at lower, more economical speeds.

Fig. 5 shows the effect of varying the thickness of a tape and consequently the total flux $\emptyset$ which would be observed in the hysteresis loop tester. Increasing the flux $\emptyset$ by a factor of five increases the output of the lower frequencies by only 6 db or a factor of two. There is no change at the high frequency end of the spectrum. This tendency of the curves to approach one another at high frequencies was first mentioned by Kornei[4]. It may be attributed to the lack of penetration of remanent induction into the tape for short wavelengths after demagnetization forces have come into play. At a tape speed of 7.5"/sec. a 7.5 kc tone will record with a wavelength of .001". The spacing along the tape from center to center of the pole pattern is therefore .0005". In a thick tape after demagnetization very little contribution to the remanent flux from depths greater than .0005" would be expected. It is therefore immaterial for short wavelengths after the demagnetization equilibrium has been established whether the original flux distribution penetrated the tape to a depth of one mil or one inch. Similarly, it should be immaterial from the standpoint of output at high frequencies whether a tape be one or two mils thick. There is no reason to assume that bias frequency flux in the recording gap does not penetrate as deeply into the coating as the audio frequencies. The penetration effect observed is the result of the geometry of the flux after demagnetization.

Fig. 6 illustrates results obtained from conditions which were identical in all respects except that the value of the remanence differed by a factor of five. The predicted increase of 14 db at low frequencies is found. In this case, the high frequency determinations are questionable. Although the curves approach one another at 10 kc, because of the inaccuracy of the measurement it cannot be concluded that they prove the prediction that a change in remanence has a smaller effect on the output at high frequencies. What may certainly be concluded is that *Figs. 5* and *6* show B_r rather than $\emptyset$ to be more nearly the determining factor in the output of tape.

Fig. 7 shows the effect on frequency response of bias current variations. As will be seen later the output curve as a function of bias current develops a sharper peak at high than at low frequencies. As a result a high value of bias current causes a drooping characteristic at the higher frequencies. The bias of 11.6 ampere turns was chosen deliberately to be very high to illustrate the point.

Noise

One of the more interesting studies made on a loop tester is that of the spectral distribution of noise. Since some aspects of the distribution serve to illustrate the behavior of modulation or under-signal noise, it may be well to consider such curves. *Fig. 8* shows data taken with a Brush KR919 reproducing head on a good sample of German Type C tape driven at a speed of 21"/sec. Curves *a* and *c* have been smoothed off peaks attributed to power frequencies in the output amplifier and to pick-up from the

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[3] Lynn C. Holmes, "Some Factors Influencing the Choice of a Medium for Magnetic Recording," *J. Acoustical Soc., 19*, 395, 1947.

[4] Otto Kornei, "Frequency Response of Magnetic Recording," *Electronics 20*, 124-28, August 1947.

motor drive. All measurements were made on the 30-cycle half band width setting of a Hewlett Packard Harmonic Wave Analyzer. The noise distribution after an a-c erase is shown by Curve *a*. Curve *b* shows the distribution after a saturating d-c wipe. The effect of the d-c wipe has been that of increasing the noise level at all frequencies. Curve "*c*" shows the distribution of noise after applying an a-c wipe and recording a moderately strong 400-cycle note on the tape. It will be seen that, in addition to the presence of the fundamental and the third and fifth harmonics, a broad distribution of noise has been recorded. For frequencies well above 400 cycles the effect of recording has been the equivalent of wiping with a d-c field somewhat less than that required for saturation. At frequencies below 400 cycles the noise drops off to approach the a-c erased level.

Two rather striking features of the modulation noise are: the small peak located at 800 cycles or the second harmonic point, and the very substantial noise contributions in the neighborhood of the 400 cycle peak. The curve has not been corrected for the pass band of the analyzer, but it may be stated that the contributions near the peak greatly exceed the filter correction. As Holmes[1] has shown, the amplitude of the under-signal noise as a function of a recorded d-c field increases with the field up to a saturation value. Any portion of the 400 cycle wave may be considered to be the application of an instantaneous d-c field accompanied by a corresponding value of the under-signal noise. The greatest value of the noise will occur at the peaks of the recorded induction, falling to zero as the induction goes to zero. The modulation envelope for this noise distribution has therefore twice the frequency of the recorded note, and the small peak at 800 cycles is believed to represent this modulation frequency.

Chapin[5] has offered an explanation of the noise in the neighborhood of the parent frequency. Unfortunately, the abstract of the paper does not present his theory completely, however, the author understands it to be based on sum and difference frequencies between noise at lower frequencies and the parent 400 cycle frequency.

The noise developed during recording has come to be known as under-signal or modulation noise. The scale of *Fig. 8* was chosen to illustrate the noise, and the reader should note that the peak of the fundamental lies about 50 db above the d-c wipe level. The maximum 700 cycle signal at 2.5% distortion to over-all noise for the tape was 68 db while the signal to total d-c wipe noise was 46 db.

When a new tape is examined, the noise level is found to be quite low. It is frequently stated that wiping such a tape increases the noise background. While this may actually be observed, it usually may be traced to one or more of three difficulties. The erase fields are not sufficiently strong to saturate the tape or the erase head design does not allow for the many decreasing alternations in the field required for a good wipe. The wipe may have a d-c component which will result in recording the d.c. as "idealized" magnetization. This will result in under-signal or modulation noise. The d-c component of the wipe may be caused by a non-symmetrical wave form in the oscillator, the unbalanced plate current of a push-pull amplifier coupled directly to the head or by permanent magnetization or the erase head core. If these wipe difficulties are avoided, it is possible to reduce the noise background to a point lower than that of new or virgin tape.

Similarly, noise contributions may arise as the result of passing the tape over the recording head. Permanent magnetization of the recording head, a d-c component in the bias current or asymmetry of the wave form give rise to modulation noise through recording of the d-c component.

Permanent magnetization of the playback head gives rise to noise by two processes. First, after passing the head, the tape will have been magnetized and modulation noise developed for the next playing. Second, during play the flux in the magnetized head varies with the reluctance of the gap. Thus, in addition to magnetization, any variations in the coating material cause a variation in gap reluctance which will show up as noise.

There are conflicting opinions regarding the possibility of generating noise on a neutral tape by passing it over a recording head which carries bias but not audio excitation. Some observers find the noise level to have increased under these conditions. Equally careful observers find that by removing any trace of a d-c field component from the recording head the noise level remains unchanged over that of the erased tape.

The noise, if present and not due to a d-c component of the recording field, must be attributed to modulation noise caused by the bias frequency. While the data of *Fig. 8* may be considered to be reliable for region of frequencies above 200 cycles, the readings below are not sufficiently accurate to draw positive conclusions. The modulation noise curve is shown approaching the a-c wipe curve at low frequencies. The fact is that it is certainly well below the d-c wipe curve, but we cannot be certain it falls off as rapidly as shown. Unfortunately, this prevents our drawing conclusions from

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[5] D. M. Chapin, "Measurement and Calculation of Under-Signal Noise in Magnetic Recording." Program 33rd Meeting Acoustical Soc. Am.

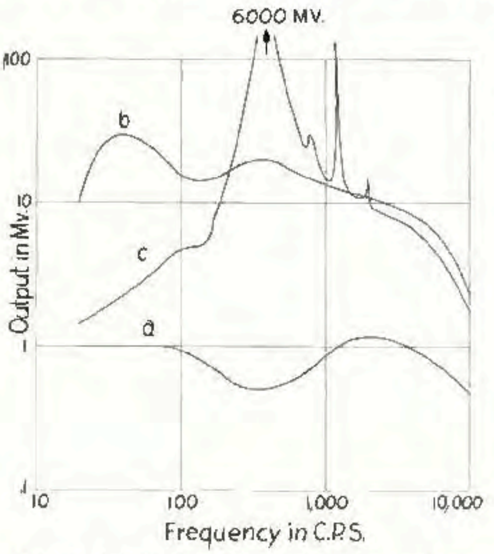
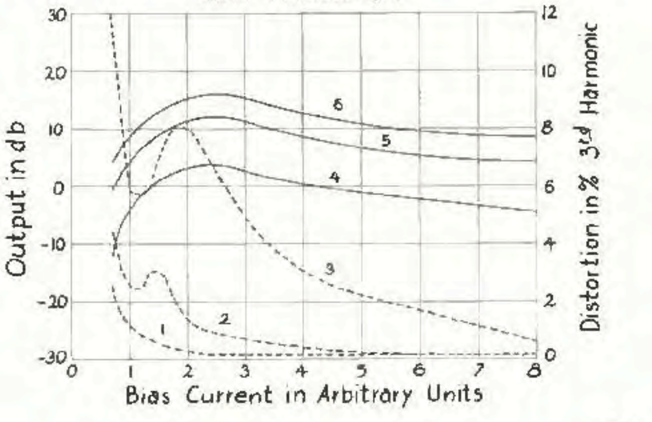


Fig. 8 (left). Noise analysis on a German tape showing the distribution for a) an a-c erase, b) d-c wipe, and c) the noise developed upon recording a 400 cycle signal. Note that the values below 200 cycles on Curve "c" are not dependable in detail but indicate the trend.

Fig. 9 (below). The third harmonic distortion and the output at 1000 cycles, 9.2" sec is shown to vary with the bias current. Distortion at 1) 5 db, 2) 10 db and 3) 20 db input levels. Output at 4) 5 db, 5) 10 db and 6) 20 db input levels. American tape.



this curve as to the possibility of a supersonic bias generating lower frequency audible noise.

Distortion

Intermodulation distortion measurements have been made on recording media by at least three laboratories, but for one reason or another this method of evaluation has not been generally adopted. When distortion is considered in tapes or wires, it is usually harmonic or amplitude distortion which is meant.

If a magnetic medium is saturated by a d-c wipe and the recording is made with either a-c or d-c bias, the operation is performed on an asymmetric transfer characteristic. This permits both even and odd harmonics to develop. In addition to the lower noise levels generated, the use of a-c bias on a tape erased to a neutral condition provides for operation on a symmetrical transfer characteristic curve which eliminates the even harmonics. Thus we see in *Fig. 8* with the exception of a small contribution to the second harmonic attributed to the modulation frequency of the under-signal noise, the harmonics observed are the third and fifth.

It is interesting to note at this point that one form of distortion which may be recorded is the beat frequency of this fifth harmonic with the bias frequency. If a 30 kc bias is used and we record say a 6,050-cycle audible tone, a 250-cycle beat note appears as distortion. This gives rise to the very practical rule that the bias frequency be at least five times that of the highest frequency one expects to record.

Returning to the subject of harmonic distortion we find two methods in general use for its evaluation. The first employs the conventional 400-cycle distortion meter which has a flat rejection filter on the band from 350 to 400 cycles. A 400-cycle note is recorded and the output through the filter measured as total distortion. Because of the peculiarities of modulation noise, this practice may be questioned, since from *Fig. 8* we may deduce that appreciable contributions to the modulation occurring near 400 cycles but outside the rejection band of the noise meter, will be counted as harmonic distortion. To this will be added the modulation noise contribution generated at all higher frequencies. The second method, which has tentatively been adopted in this laboratory, is the measurement of the third harmonic component on a wave analyzer. The fifth harmonic is usually negligibly small.

Fig. 9 shows the per cent third harmonic distortion as a function of a-c bias for recording on a demagnetized American tape. Output curves are also plotted in accordance with the practice introduced by Holmes[1]. It will be seen that maximum output is found in a region of bias for which distortion is high and lower distortion must be obtained by sacrifice of output. At first glance the regions of low distortion at low bias values may appear attractive. For two reasons they should not be used: first, they represent sharp minima which occur at different bias values for different recording levels, and second, they correspond to very low output levels. These minima correspond to recording on the toe developed in a transfer characteristic for the under-biased condition. It is the situation which causes disappointing results when high coercive force American tapes are used on machines whose bias is set for good results on low coercive force German tape. The proper condition for bias is a compromise between distortion and output on the portion of the curve beyond maximum output. Here the bias value is not critical, i. e., small shifts in bias will not cause large changes in distortion.

Recording on a machine designed with a sharp high frequency cut-off develops its distortion only at low frequencies. Suppose we expect to record up to 10 kc and provide a sharp cut-off in the output amplifier at this point. Fifth harmonics of 2000 cycles and third harmonics at 3333 cycles and above are eliminated. At high frequencies distortion may be neglected and output alone considered in choosing the bias.

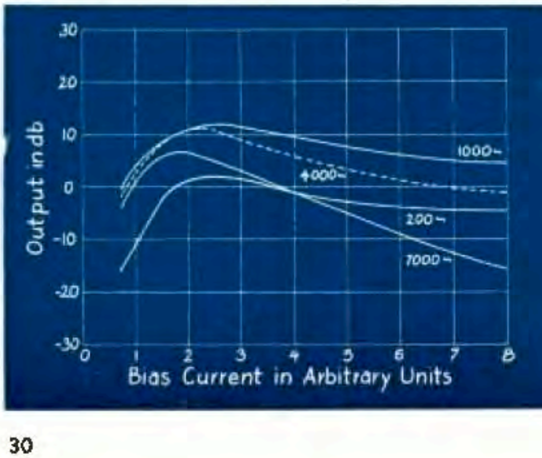
Fig. 10 shows the output of a tape as a function of bias current for a number of frequencies. It will be seen that at the higher frequencies the fall from maximum output is steeper than at low frequencies. These observations will be found to correlate with the curves of *Fig. 7*.

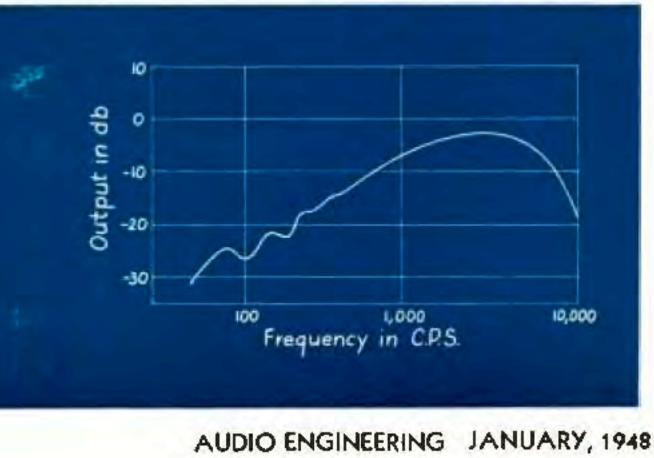
One form of distortion inherent in wire recording does not occur in tape. This is the effect of rotation of a wire on high frequency response. In the "U" shaped recording gap through which wire travels, only the portion of the wire in contact with the head is magnetized at high frequencies. This corresponds to the penetration effect in tape (*Fig. 5*) as a function of wavelength. If on playback the wire is rotated 180°, the weakly magnetized portion contacts the reproducing head resulting in serious deterioration of high frequencies. If wire is used carefully, unless a break occurs and splicing is required, there are only accidental forces which tend to rotate the wire. There is some probability that upon repeated playback the orientation remains essentially the same.

Fig. 11 shows a second effect in wire recording which causes non-uniform increase in response with increasing frequency at the lower end of the spectrum. The non-linearity of the frequency response at low frequencies is attributed to poles arriving at and leaving the reproduce head simultaneously. Some flux from these poles which is by-passed through the pick-up coil may aid or oppose the flux pick-up in the gap. That the effect should occur in wire and not tape is attributed to the surface area of wire being small compared with tape. This allows for precision contact of wire entering and leaving the head. The

[Continued on page 46]

Fig. 10 (left). An American tape used to illustrate the effect on output caused by bias variations at different frequencies at the same level (10db) of recording. Fig. 11 (right). Showing the irregularities in the response curve of a wire recording. These variations from linearity are not observed for tape.





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greater width of the tape allows an uneven approach and departure contact which averages out the flux return. If this explanation is correct, the same irregularities should be observed in tape if a very narrow recording track is used. This experiment has not been reported.

Printing or signal transfer from a recorded turn to an adjacent turn of the medium on the storage roll exists in both wire and tape. Because of the separation of the active layers of a coated tape by the magnetically inert backing some reduction, about 6 db. is obtained in signal transfer in tape as it is used over the situation in which active layers of tape come in contact. The much greater reduction which might be expected due to the physical separation of active layers is partially lost because of pole geometry. The relatively long line of poles formed across the tape during recording, which results in greater output than in a 4 mil wire of comparable magnetic properties, also results in somewhat stronger fields available for printing. In either medium the effect falls off exponentially with the level of the original recording. It may be shown that the resulting transfer is not appreciable in wire if the recording level is kept below the overload point. Tape may be expected to exhibit 6 db less in transfer than a wire of comparable magnetic properties.

Conclusion

The author announced his intentions of including in this review a discussion of equalization. The complexity of the subject together with a rapidly approaching dead-line rules out its consideration at this time. For information on equalization, the reader may see two excellent papers partially devoted to the subject.[6,7]

Finally, the author wishes to express his indebtedness for many of the ideas presented in these articles to the friends with whom he has had the opportunity to discuss magnetic recording. These are R. Herr of Minnesota Mining and Manufacturing Company, Lynn C. Holmes of Stromberg-Carlson Company, S. M. Rubens of Engineering Research Associates and R. B. Vaile, Jr. and R. E. Zenner of Armour Research Foundation.

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[6] L. C. Holmes and D. L. Clark, "Supersonic Bias for Magnetic Recording," *Electronics*, p. 126, July 1945.

[7] A. E. Barrett and C. J. F. Tweed, "Some Aspects of Magnetic Recording and Its Application to Broadcasting," *Jour. I.E.E.*, p. 265, March 1938.