Intermodulation Distortion in Tape Recording*

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The causes of intermodulation distortion in magnetic tape recording are discussed. A close correlation exists between harmonic distortion and intermodulation distortion measurements when the individual orders of distortion are measured separately.

It is shown that nonsymmetrical input signals can be a source of intermodulation in tape recording. A reason is suggested why our ear will tolerate high percentages of intermodulation distortion in music.

According to Helmholtz,[1] the difference tones associated with intermodulation distortion were first discovered in 1745 by Sorge, a German organist. It was quite natural that a musician should first publicize them since our ear, being nonlinear, will create the many spurious tones that comprise intermodulation distortion. Helmholtz, in the 1850's, discovered the IM sum tones, which are more difficult to hear because of the masking effect of the harmonics.

Our desire to look a little deeper into IM distortion originated with an attempt to locate the causes for IM in a recording of an electric guitar. A passage from the recording was made into a loop and a wave analyzer was used to determine the amplitude of the various components. Several unwanted tones were noted. We then attempted to duplicate these spurious tones using sine waves recorded at the same frequency and peak-to-peak level as the original recording. A discrepancy between the two sets of data influenced us to look closer at IM distortion.

Intermodulation distortion can only be created by mixing two frequencies in a nonlinear system: a single frequency will only produce harmonic distortion. The many extra frequencies associated with IM can be obtained by substituting $e = E_1 \sin \omega_1 t + E_2 \sin \omega_2 t$ into the power series of the following transfer function:[2,3]

$$E_{out} = a_1 e + a_2 e^2 + a_3 e^3 + a_4 e^4 + \ldots.$$

The first term in the series results in the desired output signal. The second term of the expansion produces second harmonic distortion and the first order sum and difference tones. The third term produces third harmonic distortion and the second-order sum and difference frequencies, etc. Table I lists the components resulting from the first, second and third order effects. If the series expansion is continued to the higher orders, it becomes apparent that IM products occur at regular intervals and constitute a series. This interval seems to bear a relationship to the ratio of the fundamental frequencies and is always equal to or smaller than the lowest of the frequencies. For example, fundamental frequencies of 100 and 150 cps will produce IM products at 50 cps intervals. Luckily, the higher order products are usually greatly attenuated. (There has been some confusion in the literature concerning whether the IM products resulting from the second term in the expansion should be called first order or second order. I am using the convention established by Helmholtz that calls these signals first order products.)

TABLE I. Frequency components from a nonlinear function (f_1 and f_2 applied).

1st Term	2nd Term	3rd Term	4th Term
f_1	f_1	f_1	f_1
f_2	f_2	f_2	f_2
	$2f_1$	$3f_1$	$4f_1$
	$2f_2$	$3f_2$	$4f_2$
	f_1-f_2	$2f_1-f_2$	$3f_1-f_2$
	f_1+f_2	$2f_1+f_2$	$3f_1+f_2$
		$2f_2-f_1$	$3f_2-f_1$
		$2f_2+f_1$	$3f_2+f_1$
			$2f_1-2f_2$
			$2f_1+2f_2$

In the tape recording process, the second order products

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* Presented October 17, 1962 at the Fourteenth Annual Fall Convention of the Audio Engineering Society, New York.

1. H. L. F. Helmholtz, *Sensations of Tone* (Dover Publications Inc., New York, 1954), pp. 152-173.
2. F. Langford-Smith, *Radiotron Designers' Handbook* (Radio Corporation of America, Harrison, N. J., 1954), pp. 62, 611.
3. J. S. Aagaard, "An Improved Method for the Measurement of Non-linear Audio Distortion," *IRE Trans. on Audio* AU-6, 121, (November-December, 1958).

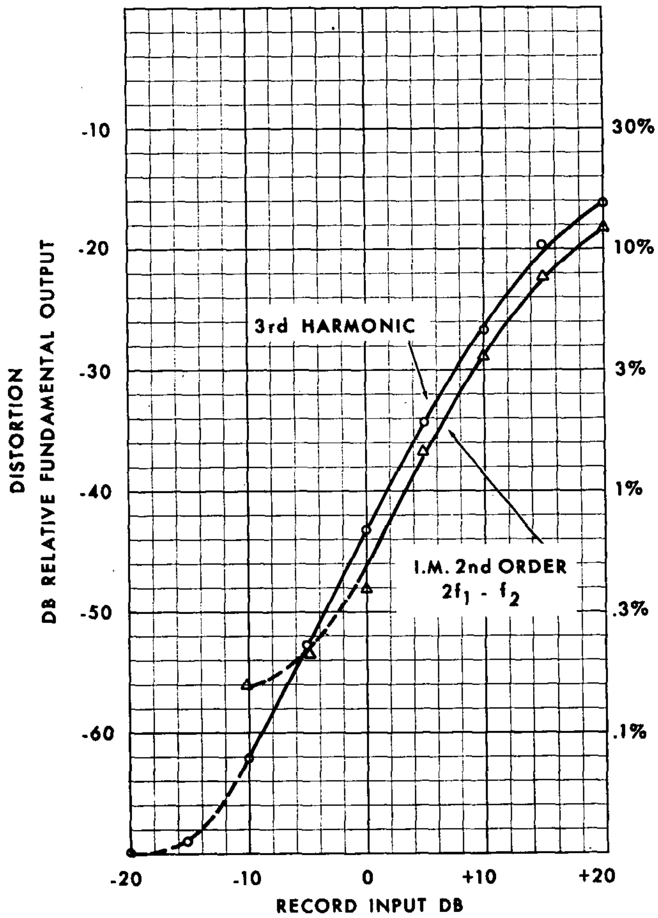

Fig. 1. Third harmonic distortion and one second-order intermodulation difference signal as a function of record input signal.

(third harmonic distortion) will normally predominate. They are caused by the magnetic tape itself. Assuming that the amplifiers contribute negligible second order products, the only factors that will change the amplitude of these effects will be the type of tape, the bias current, and the absolute level of the magnetizing force.

Theoretically, the first order effects should not be present in a tape recording. On a practical level, they may be caused by any of the following: 1. Amplifier nonlinearity; 2. Unsymmetrical bias waveform; 3. Magnetized heads; and 4. dc leakage current in the record head.

Most professional tape recorders have a noise balance control that balances bias waveform or adds a small dc current through the record head to balance out a nonsymmetrical bias waveform. It is quite often adjusted to cancel amplifier distortion, and, on occasion, is maladjusted to completely cancel the distortion in an audio oscillator connected to the input.

Figure 1 shows a plot of third harmonic distortion and second order IM distortion *vs* input to the record amplifier. Zero on the X axis is equivalent to the operating level signal from an Ampex standard tape. This is the nominal 1% distortion point. In all of the curves the following conditions apply: 1. Bias set to peak at a long wavelength; 2. vu meter disconnected so it would not contribute second order products; 3. IM measurements made at the same peak-to-peak voltage input as the single sine wave used for harmonic measurements. Therefore, the input vu meter reading for harmonic measurements is 3.8 db above the reading for IM; 4. Only one difference tone has been plotted. Assuming flat frequency response and equal input fundamentals, the amplitude of the sum and difference tones in any particular order will be the same; 5. Harmonic measurements made at 500 cps, IM made with tones of 400 plus 500 cps; 6. The dotted portions of the curve show approach to the noise level and are in doubt.

Figure 1 shows a close correlation between the amplitude of the harmonic distortion component and the amplitude of the IM difference tone. They both rise with the square of the input signal until tape saturation is approached. In other words, a 6 db rise in input results in a 12 db increase in unwanted tone/fundamental ratio.

Figure 2 shows a plot of second harmonic distortion and

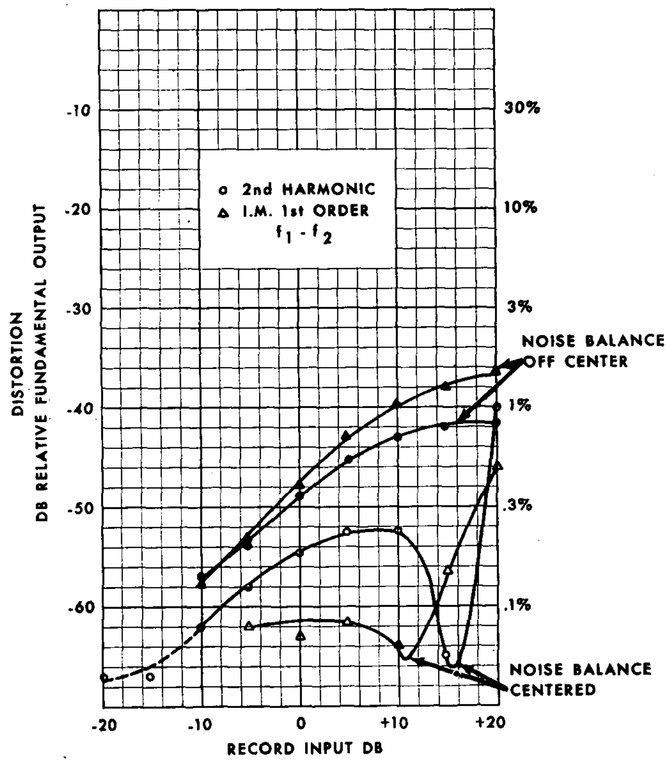

Fig. 2. Second harmonic distortion and the first-order intermodulation difference signal as a function of record input.

first order difference tone, both with noise balance centered (symmetrical bias waveform) and with it maladjusted slightly. In the balanced case the effects of distortion cancellation can be seen. The null is quite sharp in the harmonic distortion curve and probably results from cancellation with amplifier distortion. The IM null occurs at a different level and could be influenced by higher order difference tones that coincide in frequency. When the noise balance is maladjusted, the distortion caused by the asymmetrical bias predominates and the cancellation disappears.

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When the first-order effects are caused by a single source, both the percent harmonic distortion and the percent difference tone increase at an approximately linear rate—a 6 db increase in input gives a 6 db increase in the unwanted-signal/fundamental ratio. As in the case of second order effects, the correlation between IM and harmonic distortion is quite good.

Figure 3 shows a plot of first order difference tone *vs* bias symmetry. This curve was obtained by measuring IM as the bias oscillator balance control was varied through its null position; the second harmonic component of the bias waveform was used as an approximation of bias symmetry. A sharp null in IM occurs at a point near the null of bias second harmonic distortion. The lack of coincidence between the nulls shows either distortion cancellation or poor correlation between bias symmetry and bias second harmonic distortion.

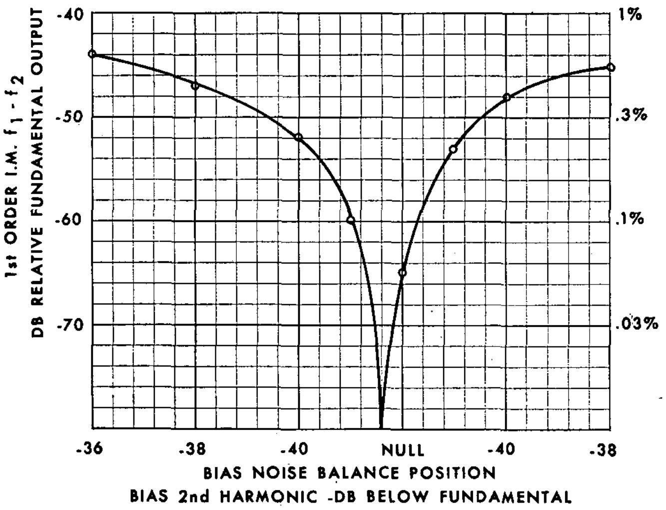

FIG. 3. First-order intermodulation distortion as a function of the second harmonic content of the bias waveform.

It would appear that there is a discrepancy between the data in Figs. 1 and 2 and a SMPTE IM measurement: the SMPTE might show 10% IM distortion where Fig. 1 shows less than 1%. This is because such a comparison is unwarranted—no correlation can exist. All of the present common IM measurement techniques leave much to be desired when applied to tape recorders. The SMPTE method that records a low-frequency fundamental plus a high frequency in the ratio of 4:1 reads the rms sum of the distortion components. It is a good check for the low-frequency linearity of the tape recording but does not separate one order of distortion from another and tells nothing about the high-frequency linearity. The CCIF method, which records two high frequencies and measures the first order difference product f_1-f_2, fails to consider the second order and higher products. The writer feels the only adequate way to evaluate a tape recorder is to measure separately a component from each of the orders of distortion. As seen from Figs. 1 and 2, harmonic distortion measurements express system nonlinearity as well as IM measurements. It is quite adequate to use the harmonics as a measurement of linearity if the following points are remembered: 1. The distortion in the signal generator must be lower than the expected distortion of the equipment (this necessitates filters); and 2. The harmonics being measured must lie in the passband of the system.

When we made the comparison between a guitar recording and its sinewave equivalent, one glaring discrepancy existed: there was a first order difference tone at the difference frequency of the fundamentals which appeared in the musical passage, but not in the sinewave duplication. It was determined that this was caused by the nonsymmetrical nature of the musical tone—the positive peaks were higher than the negative peaks. Figure 4 shows the results of a test to prove this theory. A sinewave was mixed with a rectangular wave whose pulse width could be varied. The second harmonic distortion of the sinewave was plotted *vs* the pulse-width-to-pulse-period ratio. The first order nonlinearity increases as the wave shape, starting from a sinewave, becomes asymmetrical due to the rectangular pulse. The distortion reaches a maximum and returns to the same value as the original sinewave when the rectangular pulse becomes a symmetrical squarewave. At the top of the graph, the waveshapes applied to the input are pictured, showing how they shift with respect to the zero axis as the symmetry is varied. This phenomenon seems understandable since this unsymmetrical signal is mixed with the bias in the recording process. If the lopsided input signal is of sufficient amplitude, this will result in the combined signal being unsymmetrical. Figure 3 showed how the first order distortion increased as the bias wave became unsymmetrical. It seems logical to expect unsymmetrical musical tones to have a similar effect.

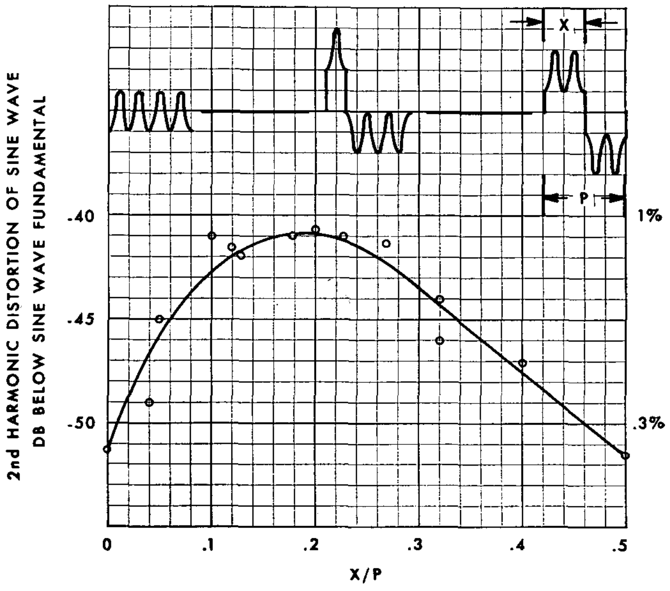

FIG. 4. Second harmonic distortion of a sinewave mixed with a rectangular wave as a function of the symmetry of the rectangular wave. Sinewave: 3 v peak-to-peak. Rectangular wave: 6.5 v peak-to-peak.

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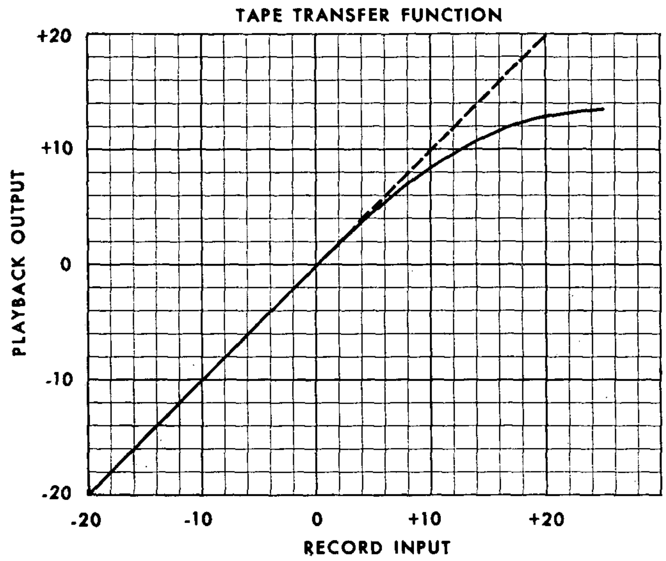

FIG. 5. Playback output of a 500-cps signal at 15 ips as a function of record input, using a typical professional magnetic tape.

One begins to wonder how one can even begin to make a usable recording with all these unwanted distortion products present. The answer is that the distortion products would never be noticed if the program peaks were kept within the linear region of the tape transfer function—no farther than "operating level." Figure 5 shows this transfer function. However, the dynamic range of tape is limited, so it is necessary to record peaks into the nonlinear regions.

It has often been stated in the literature that IM is objectionable because the unwanted tones are inharmonic.[4] It is true that the IM products do not usually coincide with harmonics of the fundamentals, but do they always produce discord? In case of recording sound effects where no harmony exists, IM will completely ruin a high-level recording. The recording of jangling keys is a case in point. However, music generally follows certain rules of harmony in order to sound pleasing.[5] In general, to sound well when played together, frequencies must be related to each other by a fraction of small integers. More specifically, the accepted theory originated by Helmholtz states that tones are harmonious or consonant as long as their fundamental and overtones do not produce beats. Beats are a familiar phenomena to us all but are sometimes confused with the first order difference tone associated with intermodulation. Beats are an interference type phenomenon which will result when two frequencies are mixed in a linear or nonlinear system.[5,6] The result to the ear and as viewed on an oscilloscope is a signal varying in amplitude at the beat rate f_1-f_2. The wave analyzer will not discover a signal at the beat rate frequency. On the other hand, the IM difference tone is created by a nonlinear system and thus can be detected.

4. F. Langford-Smith, *op. cit.*
5. James Jeans, *Science and Music* (Cambridge University Press, London, England, 1961), pp. 46-51, 152-159.
6. A. H. Benade, *Horns, Strings and Harmony* (Doubleday and Co., Inc., Garden City, N. Y., 1960), p. 77-78.

One possible explanation for the toleration of IM distortion in music is that these spurious tones may not be as dissonant as was originally thought. Table II shows the frequency ratio of the IM products for four harmonious musical relationships—the octave, the fifth, the fourth, and the major third, arranged in order of decreasing harmony. In all four cases, the IM products are related to the fundamental by fractions of reasonably small integers. In the octave, all distortion products coincide with notes of the musical scale; in the musical fifth, only one second order sum tone fails to land on a musical note; in the fourth, the first-order sum tone and one second-order sum tone miss the scale; the two second-order sum tones in the major third fail to coincide with the scale. In all of these cases, at least four of the six IM products are relatively harmless. It therefore follows that if the music is harmonious there is a good chance the IM products will also be harmonious and not too noticeable. A musician will probably find fault with this explanation, bringing out that just because the unwanted notes fall on the scale they will not necessarily sound pleasing. However, if these notes do coincide with the scale, there is a good chance that they will be masked or only dissonant enough to produce a slight roughening of the selection. A musician may also note that the frequency relationships in Table II apply to the pure scale and that most musical selections are played in the even-tempered scale where the notes are not arranged as fractions of small integers. However, it should be remembered that the even-tempered scale is a compromise and results in beats at a rate slow enough not to be objectionable. It would appear that since these notes are not objectionable, the distortion products would be no more objectionable on the even-tempered scale than on the ideal scale.

TABLE II. Distortion analysis for four musical relationships.

DISTORTION ANALYSIS OF MUSICAL OCTAVE
FREQUENCY RATIO 2:1 ($f_2 = 2f_1$)

FREQ. RATIO RESPECT TO f_1	0	1	2	3	4	5	6
MUSICAL NOTE		C	C	G	C	E	G
FUNDAMENTAL		f_1	f_2				
2nd HARMONIC			X		X		
3rd HARMONIC				X			X
1st ORDER IM		X		X			
2nd ORDER IM	X			X	X	X	

DISTORTION ANALYSIS OF MUSICAL FIFTH
FREQUENCY RATIO 3:2 ($f_2 = 3/2\ f_1$)

FREQ. RATIO RESPECT TO f_1	$\frac{1}{2}$	$\frac{2}{2}$	$\frac{3}{2}$	$\frac{4}{2}$	$\frac{5}{2}$	$\frac{6}{2}$	$\frac{7}{2}$	$\frac{8}{2}$	$\frac{9}{2}$
MUSICAL NOTE	C	C	G	C	E	G		C	G
FUNDAMENTAL		f_1	f_2						
2nd HARMONIC				X		X			
3rd HARMONIC						X			X
1st ORDER IM	X				X				
2nd ORDER IM	X			X			X	X	

DISTORTION ANALYSIS OF MUSICAL FOURTH
FREQUENCY RATIO 4:3 ($f_2 = 4/3\ f_1$)

FREQ. RATIO RESPECT TO f_1	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{3}{3}$	$\frac{4}{3}$	$\frac{5}{3}$	$\frac{6}{3}$	$\frac{7}{3}$	$\frac{8}{3}$	$\frac{9}{3}$	$\frac{10}{3}$	$\frac{11}{3}$
MUSICAL NOTE	F	F	C	F	A	C		F	G	A	
FUNDAMENTAL			f_1	f_2							
2nd HARMONIC						X		X			
3rd HARMONIC									X		
1st ORDER IM	X						X				
2nd ORDER IM		X			X					X	X

DISTORTION ANALYSIS OF MUSICAL MAJOR THIRD
FREQUENCY RATIO 5:4 ($f_2 = 5/4\ f_1$)

FREQ. RATIO RESPECT TO f_1	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{4}{4}$	$\frac{5}{4}$	$\frac{6}{4}$	$\frac{8}{4}$	$\frac{9}{4}$	$\frac{10}{4}$	$\frac{12}{4}$	$\frac{13}{4}$	$\frac{14}{4}$
MUSICAL NOTE	C	G	C	E	G	C	D	E	G		
FUNDAMENTAL			f_1	f_2							
2nd HARMONIC						X		X			
3rd HARMONIC									X		
1st ORDER IM	X						X				
2nd ORDER IM		X			X					X	X

However, there are also times in music when IM can be quite obnoxious. It can be seen from Table II that there is normally one first-order difference tone and one second-order difference tone below the lowest fundamental fre-

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quency. While these tones are not usually dissonant, the musician who made the original recording knows he did not play those notes. In addition, the second-order sum tones can be a very irritating source of disturbance when the recording nears tape saturation. The tones in themselves seem quite innocent, being related to the fundamentals by small fractions. But in some cases these sum tones will beat, causing a "buzz" with pure tones or a familiar "fuzziness" in complex tones. Here the beat is the trouble-maker. If either of the sum tones is removed with a filter, the buzz will disappear. This buzz will not always occur. To be objectionable, beats must bear a particular relationship to the fundamental frequency causing them.[7] A 50 cps beat cannot be heard between 100 and 150 cps but is highly objectionable between fundamentals of 600 and 650 cps. In the case of a high-level recording of 500 and 400 cps, the fundamental beat is not noticeable but the beat between the second-order sum tones at 1300 and 1400 cps produces a loud buzz.

In conclusion, then, what can be done to reduce distortion? First, one should make sure that the bias is adjusted properly for the tape being used. (Underbias, sometimes used to increase high-frequency response, causes an increase in distortion.) Second, the bias waveform symmetry should be adjusted to minimize first-order effects, making sure that amplifier distortion and magnetized heads are not compounding the problem. The remaining distortion should then be second-order products caused by the tape. The only way this distortion can be reduced is to lower the record input. A 5 db reduction in level will result in a 5 db degradation in signal-to-noise ratio but a 10 db improvement in signal-to-distortion-product ratio. And it still appears that the best instrument for making this distortion-noise compromise is the trained ear.

7. James Jeans, *op. cit.*

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Acknowledgements: to Les Paul for being the best IM distortion analyzer in the industry today, and J. G. McKnight for suggesting that intermodulation distortion does not have to be dissonant.

THE AUTHOR

Robert Z. Langevin was born in 1925 in California. He attended the University of Colorado and the University of Michigan, where he received the B.S.E.E. degree in 1946.

Through 1950 he worked for companies founded by his father: Langevin Manufacturing Corporation, and Carl Langevin, Inc. In 1951 he joined Ampex Corporation and became associated with the engineering of audio tape recorders. In 1960 he served with Vega Electronics Corporation as project engineer for wireless microphones. He rejoined Ampex in 1961, and is now an electronic engineer in its Audio Division.

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

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All manuscripts received by August 16th (remember to send single-spaced typed copy) will be preprinted in time for the Convention at no charge to the author. Address to Secretary's Office, P.O. Box 12, Old Chelsea Station, New York 11.