Our next speaker is well known to most of us, Mr. Ken Simons, Vice President of Research and Development of The Jerrold Corporation. Mr. Simons received his BSc in electrical engineering at the Moore School of Electrical Engineering at the University of Pennsylvania. He has been active in radio since 1928, active in television since 1938 and has been active in CATV since 1951.

It is with great pleasure that I present Mr. Ken Simons to talk about "Distortion in CATV Amplifiers." Mr. Simons. (Applause)

MR. KEN SIMONS (Jerrold Electronics Corporation): Before I begin I would like to comment to Alan Ross that we are delighted to have him refer to our Channel Commander by name if he has something nice to say about it. Otherwise he should call it a headend converter. (Laughter)

THE FUNDAMENTALS OF DISTORTION IN CATV AMPLIFIERS

by Ken Simons, Jerrold Corporation

Introduction:

Distortion in sound reproducing equipment is familiar to anyone who has heard a worn-out jukebox, or an overloaded public address system. This harsh, unpleasant sound presents the essential nature of all distortion: What comes out of the system is different from what went in! In a CATV system distortion does not show up in the same way, but it is present, and it places restrictions on system operation which must be understood if it is to be intelligently planned and operated.

The amplifiers used in CATV have only one intended function: to increase the signal levels. The other things they do, the differences they generate between the outgoing signals and the incoming signals are distortion. What forms does this distortion take? Several effects properly called distortion, such as the addition of noise to the signal, hum modulation and variations in amplifier frequency response are not the subject of this paper. It is concerned with only one kind of distortion: effects due to the same causes that create "harmonic distortion" in audio amplifiers. This distortion is due almost entirely to amplitude non-linearity in the transistors. Its worst effect is cross-modulation, crossing over of the modulation from one channel to another, which causes "windshield wiper" effects in the picture. Other effects include harmonics, where an unwanted signal is generated at a frequency which is some multiple of the frequency of a wanted one; and beats, where two or more wanted signals combine to generate an interfering one. A study of distortion will help in understanding how CATV amplifiers can be operated to avoid these problems.

Distortion less Amplification:

Perhaps the simplest way to describe amplitude distortion is to say what it is not. A distortionless amplifier would be one which increased the amplitude (voltage swing) of the input signal without changing its waveform. Suppose, for example, an amplifier could be built so that the output voltage, at each instant, was exactly 10 times the input voltage. A graph showing the output voltage plotted against the input voltage would be a straight line, as illustrated in Fig. 1. Such a graph is called the "transfer characteristic" or "input-output curve", for the amplifier. A transfer characteristic which is a straight line is called a "linear transfer characteristic".

Mathematically, the performance of this amplifier would be described by the equation: $e_{out} = 10\ e_{in}$; where e_{out} is the instantaneous output voltage, and e_{in} is the instantaneous input voltage. Calculating for particular voltages would give a table:

e_{in}	e_{out} (= 10 e_{in})
0	0
-0.2	-2
-0.4	-4
-0.6	-6
-0.8	-8
-1.0	-10
e_{in}	e_{out} (= 10 e_{in})
0	0
+0.2	+2
+0.4	+4
+0.6	+6
+0.8	+8
+1.0	+10

This is the table from which the characteristic of Fig. 1 is plotted.

The way in which such a linear transfer characteristic results in an undistorted output is shown in Fig. 2. A plot of the sinusoidal input voltage against time is illustrated (Fig. 2(a)). If, at each point along the time scale, the instantaneous input voltage is projected downward to the transfer characteristic (Fig. 2(b)), the corresponding output voltage is found. Projecting this to the right, and plotting against the same time scale constructs graphically the waveform of the output voltage (Fig. 2(c)). For example, when the input is 0.75 volts and decreasing (point "A"), the output is 7.5 volts and decreasing (point "B"). Since the output voltage at each time is simply ten times the input voltage, the output duplicates the input waveform. Each point on the output waveform corresponds exactly with the corresponding point on the input, so there is no distortion.

The action has nothing to do with the input voltage waveform. Whatever that waveform is, it is duplicated in the output. Fig. 3, for example, shows a similar diagram with a pyramidal input, showing how an identically-shaped pyramidal output results.

Amplication with Distortion:

Unfortunately, amplifiers that can be built using real-life transistors do not have a linear relationship between the input voltage and output voltage. Figure 4 illustrates a non-linear transfer characteristic which might be found in a real amplifier. As the input voltage swings either way from 0, the output changes along a curve which produces less and less change in output voltage as the input swings further and further from 0. In the example illustrated, were the output to continue increasing along a straight line at the same rate it follows near 0, it would reach about +20 volts when the input was +1 instead of the +10 it actually reaches.

When a varying voltage is applied to an amplifier with a characteristic of this sort, the output voltage will have a different waveform from the input voltage. Consider the examples shown in Figure 5. Figure 5(a) illustrates the output voltage waveform obtained when a sinusoidal voltage with a voltage swing between +1 and -1 volts is applied to the amplifier whose characteristic is illustrated in Figure 4. Since the transfer characteristic is symmetrical, both peaks of the output voltage are squashed by the non-linearity giving the waveform illustrated.

A 0.5 volt peak-to-peak sinusoidal voltage applied to the input of the same amplifier and biased at -0.5 volts so that it varied between 0 and -1 volts would produce an output varying between 0 and -10 volts with the waveform illustrated in Figure 5(b). The lower peak is squashed because the curve bends over at -1 volts input, the upper peak is faithfully reproduced because the curve is very nearly a straight line near 0.

Reducing the amplitude of the input voltage is 0.2 volts peak-to-peak and biasing it at 0 so that it varies between +0.1 and -0.1 volts gives the output voltage shown in Fig. 5(c). Because the signal was varying along a nearly linear part of the characteristic, this is almost an undistorted reproduction of the sinusoidal input.

It should be clear from these examples that the nature as well as the degree of distortion is dependent not only on the transfer characteristic of the amplifier but equally on the amplitude of the input signal and on the operating point (bias). Two very different and significant kinds of distortion are illustrated: one where the peaks are squashed symmetrically [Fig. 5a)] and the other where only one peak is squashed [Fig. 5b)]. In what follows these two cases will be explored more thoroughly.

Second order Distortion:

In the section on distortionless amplification, it was shown that a linear transfer characteristic could be expressed in very simple mathematical terms. The equation "$e_{out} = 10e_{in}$" says very clearly that the amplifier in question has a gain of ten times and no distortion. Since all practical amplifiers cause distortion, a sensible question is: "Can the transfer characteristic of a practical amplifier be expressed in some simple mathematical way which will allow analysis of the distortion generated?" The answer is yes, of course, and the subject of what follows is how this is done.

First, consider an amplifier which generates the kind of distortion illustrated in Figure 5(b). The transfer characteristic causing this kind of distortion can be approximated by an equation having the form "(e_{out}) equals (some number times e_{in}) plus (some other number times e_{in}^2)."

The following may help to understand how this works. Consider first the curve that results when e^2 is plotted against e. The numbers come out like this:

e	e^2	e	e^2
-1.0	+1.0	+1.0	+1.0
- .8	+ .64	+ .8	+ .64
- .6	+ .36	+ .6	+ .36
- .4	+ .16	+ .4	+ .16
- .2	+ .04	+ .2	+ .04
0	0	0	0

This curve is plotted in Figure 6. Notice that it is symmetrical about 0, curving up smoothly for both positive and negative values of e.

Next consider an example of what happens when a curve of this sort is added to a linear transfer characteristic. The output voltage is separated into two parts:

for the linear part: $e_1 = 10\,e_{in}$

for the "squared" part: $e_2 = 5\,e_{in}^2$

and for the total: $e_{out} = e_1 + e_2$

$= 10e_{in} + 5e_{in}^2$

The numbers come out like this:

e_{in}	$10\ e_{in}$	e_{in}^2	$5\ e_{in}^2$	$10\ e_{in} + 5\ e_{in}^2$
-1	-10	+1	+5	-5
-0.8	- 8	+0.64	+3.2	-4.8
-0.6	- 6	+0.36	+1.8	-4.2
-0.4	- 4	+0.16	+ .8	-3.2
-0.2	- 2	+0.04	+ .2	-1.8
0	0	0	0	0
+0.2	+ 2	+0.04	+ .2	+2.2
+0.4	+ 4	+0.16	+ .8	+4.8
+0.6	+ 6	+0.36	+1.8	+7.8
+0.8	+ 8	+0.64	+3.2	+11.2
+1.0	+10	+1.00	+5	+15

Fig. 7 shows the two curves plotted separately (a and b) and the total (c). Notice the similarity between this total curve [Fig. 7(c)], the plot of a simple mathematical equation, and the lower half of a particular non-linear transfer characteristic (Fig. 4).

Fig. 8 illustrates graphically how the introduction of a sinusoidal voltage into an amplifier having a square-law transfer characteristic results in an output of the one-peak-stretched, one-peak-squashed variety. Since this kind of distortion results from the addition to the linear characteristic of a quantity involving e^2, it is called "second order" distortion. In these terms it is said that Fig. 8 shows that "a square-law transfer characteristic (or a characteristic having second-order curvature) causes second-order distortion of the output." Observe that not only is the upper peak of the output voltage stretched by the action of the second-order distortion and the lower peak squashed, but also the entire curve is shifted upward so that its average is above 0.

Second-order Distortion by Addition of Components:

As has been shown, one way to study second-order distortion mathematically is to use a square-law equation. There is a second approach which is also very useful. This approach involves the addition of d-c and sinusoidal voltages to produce a distorted total. Figure 9 illustrates how this works. Because the "parts" or "components" that go to make up a distorted waveform are being considered, each component is given a name. This diagram shows how a distorted output can be generated by adding together three components: the fundamental component, a sinusoidal voltage having a frequency of 1 MHz (1 cycle in 1 microsecond) in this example; the second harmonic component, a sinusoidal voltage having twice this frequency, 2 MHz (2 cycles in 1 microsecond); and a positive d-c component.

Notice first that the total voltage has a waveform identical with that produced when a sinusoidal voltage is passed through the square-law characteristic of Figure 8. Now see how the three components add together in Fig. 9: At 0 time on the diagram, the fundamental component is 0, the second harmonic is at its negative peak (-2.5 volts) and the d-c component is at +2.5 volts. Adding the three together gives the total voltage which is 0. At 0.25 microseconds the fundamental has gone through one-quarter cycle to its positive maximum (+10 volts), the second harmonic component has gone through one-half cycle to its positive maximum (2.5 volts) so the three add together to produce the peak voltage of the total (+15 = 2.5 + 2.5 + 10). At 0.75 microseconds the second harmonic and the d-c are at +2.5 volts so they subtract from the -10 volt peak of the fundamental to give the squashed peak of the total (-5 = -10 + 2.5 + 2.5).

This diagram illustrates one case of a very important general principle: Any non-sinusoidal periodic waveform can be produced by adding together an appropriate combination of d-c and sinusoidal components.

Spectrum of a Voltage with Second-Order Distortion:

A very convenient way of measuring any varying voltage is to plot its "spectrum". A spectrum is simply a graph which plots in the vertical direction, the peak voltage or amplitude of each sinusoidal component and in the horizontal direction, shows the frequency at which each of these components exists. Its importance rests on the fact that "spectrum analyzers" are available which plot these diagrams automatically, providing tremendously useful tools for distortion analysis. The spectrum of a sinusoidal voltage is a single spike showing the amplitude and frequency of that voltage. Figure 10, for example, shows the spectrum of the fundamental component voltage in Figure 9. It says three things: (1) this voltage is a pure sine-wave (there is only one spike); (2) its peak amplitude is 10 volts (the vertical reading at the top of the spike); (3) its frequency is 1 MHz (the horizontal position of the spike).

Figure 11 illustrates the spectrum of the distorted output voltage of Figures 8 and 9. It shows three components: the 2.5 volt peak, 2 MHz second harmonic; the 10 volt, 1 MHz fundamental; and the 2.5 volt 0 frequency (d-c) component. (Note that most spectrum analyzers do not show d-c components so that only the other two would be displayed.)

Third Order Distortion:

In the previous section it has been shown that the kind of non-linearity which results in the "one-peak-squashed" kind of distortion can be expressed by a simple square-law mathematical equation. In very much the same way, the kind of distortion which results in both peaks being squashed can be expressed by a cube-law equation. This equation has the form: (e_{out}) = (some number x e_{in}) + (some other number x e_{in}^3). It approximates a transfer characteristic of the "both-peaks-squashed" type, as illustrated in Fig. 5(a).

Consider the curve that results when e^3 is plotted against e. The numbers come out like this:

e	e^3	e	e^3
-1.0	-1.000	+1.0	+1.000
- .8	-0.512	+ .8	+0.512
- .6	-0.216	+ .6	+0.216
- .4	-0.064	+ .4	+0.064
- .2	-0.008	+ .2	+0.008
0	0	0	0

This curve is plotted in Fig. 12. It is "skew symmetrical"; that is, the curve for negative values of e has the same shape as for positive values, but is upside down.

When this curve is added to a linear transfer characteristic, it affects both extremes in the same way, since the linear part and the "cubed" part go positive together and negative together. Consider an example:

for the linear part of the characteristic take:

$$e_1 = 10\ e_{in}$$

for the "cubed" part take: $e_3 = 3\ e_{in}^3$

to get a curve which squashes the peaks, the cubed part is subtracted from the linear part, so the total is:

$$e_{out} = e_1 - e_3 = 10e_{in} - 3e_{in}^3$$

The numbers come out like this:

e_{in}	$10\ e_{in}$	e_{in}^3	$3\ e_{in}^3$	$10\ e_{in} - 3\ e_{in}^3$
-1	-10	-1.000	-3.000	-7.000
-0.8	- 8	-0.512	-1.536	-6.464
-0.6	- 6	-0.216	-0.648	-5.352
-0.4	- 4	-0.064	-0.192	-3.808
-0.2	- 2	-0.008	-0.024	-1.976
0	0	0	0	0
+0.2	+ 2	+0.008	+0.024	1.976
+0.4	+ 4	+0.064	+0.192	3.808
+0.6	+ 6	+0.216	+0.648	5.352
+0.8	+ 8	+0.512	+1.536	6.464
+1.0	+10	+1.000	+3.000	7.000

Fig. 13 shows the two component curves plotted separately (a and b) and the total (c). Notice the similarity between this total curve, the plot of a simple equation, and the non-linear transfer characteristic shown in Fig. 4.

Fig. 14 illustrates graphically the way in which the introduction of a sinusoidal voltage into an amplifier having a "cube-law" transfer characteristic results in an output of the "both-peaks-squashed" variety. Since this kind of distortion results from subtracting a quantity involving e^3, it is called "third order" distortion. In these terms it is said that Figure 14 shows that "a cube-law transfer characteristic (or a characteristic having third order curvature) causes third order distortion of the output."

Third Order Distortion by Addition of Components:

In the foregoing it was found possible to duplicate the effects of second order distortion by adding sinusoidal components. In a similar way, the effects of third order distortion can be obtained. Figure 15 illustrates the addition of a 10 volt peak, 1 megacycle fundamental component (a) and a 1 volt peak, 3 megacycle third harmonic component (b) to produce a distorted total (c) having the same waveform as that generated by the cube-law equation illustrated in Fig. 14. Because of the 3:1 frequency relationship, the third harmonic voltage is opposite in phase to the fundamental at its positive peak with the result that the total is squashed, and is again opposite in phase at its negative peak so the total is also squashed at that time.

Spectrum of a Voltage with Third Order Distortion:

Figure 16 illustrates the spectrum of this distorted voltage. Since the distortion waveform is duplicated by the sum of two components, the spectrum shows only these two: a 10-volt-peak fundamental component at 1 MHz and a 1-volt-peak third harmonic at 3 MHz.

A "Beat"; the Sum of Two Sinusoidal Voltages of Different Frequencies:

Since a major object of this article is to investigate the effects that occur in broadband amplifiers when many "channels" are handled simultaneously, it is necessarily concerned with what happens in an amplifier when more than one sinusoidal voltage is introduced into it. Although the picture carrier on each channel is not a constant-amplitude sine-wave (since it is modulated with the picture information), a great deal can be learned about the nature of distortion in this case by temporarily pretending that it is. The first question then is: What is the waveform of the voltage resulting when two sine-waves having different frequencies are added?

To answer this question it is helpful first to consider the way in which two sinusoidal voltages add when each has the same frequency and amplitude, but they have various phase relationships. Fig. 17 illustrates several cases showing each voltage separately (a and b) and the resulting total voltage (c).

When each voltage is sinusoidal, the frequencies are identical, and the voltages are exactly in phase, the two reach their peaks at the same instant and at that time they add directly (e.g. 1.0 + 1.0 = 2.0) so the peak voltage of the total is the sum of the two components (shown as the 0° condition).

When there is a 90° phase difference between the two, the total reaches its maximum at a time when each of the components is at 0.7 of peak, so the peak voltage of the total is reduced to 0.7 of the sum of the peak voltages of the components e.g. + 0.7 + 0.7 = 1.4 (the +90° and -90° conditions) . When the two voltages have opposite phase (180° out of phase), they are equal and opposite at all times, and the total is 0 (the 180° condition).

Next consider the addition of two sinusoidal voltages having different frequencies. Figure 18 (a and b) illustrates the waveforms of two particular voltages. Each is sinusoidal, with a peak amplitude of 2 volts. One has a frequency of 5 MHz, a time-per-cycle of 1/5 microseconds; the other has a frequency of 6 MHz, and a time-per-cycle of 1/6 μsec. Thus, the former completes 5 cycles in a microsecond while the latter is completing 6 cycles.

Superimposing the two waveforms on each other Fig. 18(c) shows clearly a highly significant fact, the phase relation between them is changing constantly. Initially they are in phase (both at positive peak). After 1/4 microsecond the 5 MHz voltage has gone through 1-1/4 cycles and is 0, going negative, while the other has gone through three half-cycles and is at its negative peak. They differ in phase by 90°. After 1/2 microsecond the 5 MHz one is at its negative peak, while the 6 MHz one is at its positive peak, and they are 180° out of phase. As time goes on, they go through all possible phase relations, coming back to the "in phase" condition once each microsecond.

Now what happens when these two voltages are added? The total follows the principles illustrated

Fig. 17. When the two components are in phase, they add to produce a maximum peak voltage, when they are 180° out they cancel, and in between the peak amplitude changes from one condition toward the other. The resulting waveform is illustrated in Fig. 19(a), showing the two component voltages and the total superimposed, and Fig. 19(b), showing the total alone. The total voltage reaches a 4-volt maximum peak initially when the two are in phase, the peaks reduce on successive cycles reaching 0 after 1/2 microsecond when the two components are 180° out of phase, and building up again to a 4-volt maximum peak after one microsecond when they come back in phase again.

This "beat" voltage, the sum of two particular sinusoidal voltages, demonstrates several characteristics common to all sums of two such voltages without regard to their frequencies. One characteristic is the variation in the peak voltage of the total. For the sum of two equal voltages with <u>any</u> frequencies, the total peak voltage varies from maximum to 0 and back to maximum at a frequency which is the difference of the frequencies of the components. (In this example, the peak voltage varies at a frequency of 1 MHz = 6 - 5.) What does a spectrum analysis of the total voltage show? As indicated in Fig. 20, the analysis shows two 2-volt components, one at 5 MHz and one at 6 MHz, and that is all. How can that be? The peak of the total voltage certainly increases and decreases at a frequency of 1 MHz. Is there no 1 MHz "signal" or "component" there? The answer is that there is none, and the reason goes right back to what is meant by the term "component". A set of lines on a spectrum chart, or a statement "There are frequency components present at these specified frequencies" means only one thing: that the waveform of the voltage in question can be duplicated precisely by adding together sinusoidal voltages having the indicated amplitudes and frequencies. In the example, the initial condition showed that this waveform is generated when a 5 MHz component is <u>added</u> to an equal 6 MHz component. They were added, nothing else was added so the total voltage cannot, by definition, contain any other components. A basic principle is involved:

> Only when there is non-linear distortion are frequency components generated in the output which were not present in the input.

What about the 1 MHz variation in peak voltage? Is it "there"? Of course, it's there. It is evident on the waveform, but the fact that something (i.e. the peak voltage) in this waveform varies at a frequency of 1 MHz, does not mean that there is a 1 MHz component present. No 1-MHz sinusoidal voltage component is needed to duplicate this waveform. If the variation over a full microsecond is inspected, it can be seen that the "beat" voltage varies in such a way that it spends exactly as much time below 0 in each half cycle as it does above, so on the average there is no variation at the 1 MHz frequency.

<u>A Beat Voltage with Second Order Distortion:</u>

It has been shown that, when two sinusoidal components are fed into a distortionless amplifier, the output contains only the two original components, or saying the same thing, the output waveform is the same as that of the input. Fig. 21 illustrates again the waveform and spectrum in this case, showing how the total peak voltage varies at the difference frequency $(f_2 - f_1)$ as the phase relation between the components changes.

Now consider what happens when the two sine-wave voltages are added and introduced into an amplifier with second order distortion. Fig. 22(a) illustrates the result, the distorted waveform that occurs when a "beat" voltage (the sum of two sine-waves) is fed through an amplifier having only second order distortion.

Since the output waveform has a decidedly different shape from the input [compare Fig. 22(a) and Fig. 21(a)], it is clear that there must be components at frequencies other than the two original ones. Fig. 22(b) illustrates the five new frequency components that are added to the output voltage by second order distortion. Since the positive peaks in the output are stretched, and the negative peaks squashed, there is a general shift in level in the positive direction, and there must be a corresponding positive d-c component. Since the peaks above 0 no longer average out with the peaks below 0, there is also a component at the difference frequency $(f_2 - f_1)$. For a similar reason, there is a component at a frequency which is the sum of the frequencies of the two originals signals $(f_1 - f_2)$. And of course, each of the original signals generates a second harmonic (at $2f_1$ and $2f_2$). Thus, the spectrum of the output signal looks like Fig. 22(b) with components at the two original frequencies as well as at the five new ones.

An important conclusion can be drawn from this one example: Whenever more than one sinusoidal voltage (that is when more than one signal) is introduced into an amplifier which has second order distortion, the output will include signals at certain frequencies differing from those of the input signals. There will be a d-c component, a shift in the average collector current of the distorting stage which generally does not show up in the output, a component at a frequency which is the difference of the two original frequencies, a component at a frequency which is the sum of the original frequencies. When the original signals are modulated with picture information, each of these spurious signals will carry the modulation of both of the original signals from which it comes.

Why Second Order Distortion is Unimportant in Present CATV Systems:

Anyone who has worked with CATV equipment in the past recognizes the fact that very little attention has been paid to the problem of second order distortion. The usual amplifier specification states the noise figure, gain and cross-modulation but does not mention sum or difference frequency beats or second harmonics. The reason for this has to do with the standard channel frequency assignments established by the FCC. If one takes any pair of picture carrier frequencies in the standard 12-channel assignment, their sum or difference does not fall in any of those channels. Similarly, with one minor exception (channel 6 sound carrier), the second harmonics of all low band carriers fall between the two bands. Figure 23 shows the spectrum obtained when 12 CW signals on the normal picture carrier frequencies were introduced into a CATV amplifier at levels somewhat higher than normal operating level. This shows the spurious signals resulting from second order distortion illustrating how they fall below and between the bands, but not within the channel limits. Since this is true, second order distortion has no bad effects on an amplifier carrying up to twelve standard TV channels, and it is not normally considered in this case.

Beat Voltage with Third Order Distortion:

Figure 25(a) illustrates the appearance of the output voltage of an amplifier having third order distortion when a beat input signal similar to Figure 21(a) is introduced into the input. The squashing of the larger vertical peaks is clearly evident. A spectrum diagram showing the frequency components in the output is shown in Figure 25(b). In addition to the two original sinusoidal components (at f_1 and f_2) spurious signals occur at the following frequencies:

$2f_1 - f_2$ This falls below f_1 at a spacing corresponding to the frequency difference between f_1 and f_2.

$2f_1 - f_1$ This falls above f_2 at a spacing corresponding to the frequency difference between f_1 and f_2.

$3f_1$ and $3f_2$ These are the third harmonics and th spacing between is three times the spacing between f_1 and f_2.

$2f_1 + f_2$ This falls above $3f_1$ at a spacing corresponding to the frequency differen between f_1 and f_2.

$2f_1 + f_1$ This falls below $3f_2$ at a spacing corresponding to the same difference.

Cross-Modulation and Compression:

The spurious signals generated by third order distortion in present CATV systems. This is "cros modulation", one of two important effects of third order distortion which do not result in components at new frequencies. Each of these effects represent a change in gain at the channel frequencies rather than the generation of new frequency components. Figure 26 illustrates these effects. These spectrum diagrams illustrate the input and output components in an amplifier which has severe third order distortion. The upper diagrams illustrate the input signal components, the lower diagrams illustrate the resulting output signal components. The amplifier voltage gain, for small signal input, is 10 times. Thus, as illustrated in Figure 26(a), an input of 2 millivolts gives an output of approximately 20 milli- volts. It can be seen by inspecting the shape of any third-order distortion characteristic [Figure 13(b) f example] that the effective gain decreases as the signal amplitude increases. Thus, as shown in Figure 26(b), increasing the input signal of this ampl fier to 10 millivolts results in an output of about 90 millivolts, rather than 100 millivolts which would be obtained if the gain were not reduced by the effects o third order distortion. This effect, the reduction in gain at a single frequency as the signal amplitude increases, is called compression and results in distortion of the modulation envelope on any modulated signal going through such an amplifier. When this effect occurs in an amplifier carrying a single TV-modulated signal, it results in a squashing of the sync peaks which is called "sync compression". Figure 26(c) shows what happens when a signal is introduced at low level on another frequency. Several effects can be seen: The output level on the new frequency is somewhat below the 20 millivolt it would reach if the strong signal were not present; the strong signal output is slightly reduced by the presence of the new signal [compare (b)], and a spurious component at $2f_1-f_2$ can be seen.

As shown in Figure 26(d), increasing the second signal to full amplitude results in a further reduction in gain so that both output signals at the original frequencies are below 60 millivolts and the spurious signals increase in amplitude. The most significant effect here is that the gain on each channel is reduced not only by an increase in level on that channel but also by the increase in level on the other channel. This results in a transfer of any variation, or modulation, on one carrier to any other carriers going through the same amplifier. This transfer is called cross-modulation and represents the worst effect of non-linearity in present-day CATV amplifiers.

This effect is further illustrated in Fig. 27. Figure 27(a) shows the output signal obtained when a sinusoidal input is applied to an amplifier with a small amount of third order distortion. Figure 27(b) shows what happens when a second signal, fully modulated, is fed through the same amplifier. The output includes the modulated signal (which shows up in the frequency spectrum as a carrier with smaller sidebands on each side), the output at the frequency of the original CW signal, and two spurious sideband components which show up adjacent to the CW signal frequency as a result of third order distortion. It is clear how this distortion results in a transfer of modulation from one signal to the other.

Conclusion:

This article has attempted to describe all of the effects which result from the simplest kinds of non-linearity, second order and third order distortion, in amplifiers of the type used for CATV systems. It has shown that second order effects are generally unimportant with present-day frequency assignments and that, of all the third order effects, cross-modulation is the most important, representing the factor which limits the output level at which the amplifiers in these systems may be operated without causing disturbance to the customer's reception.

A LINEAR
TRANSFER CHARACTERISTIC

Figure 1

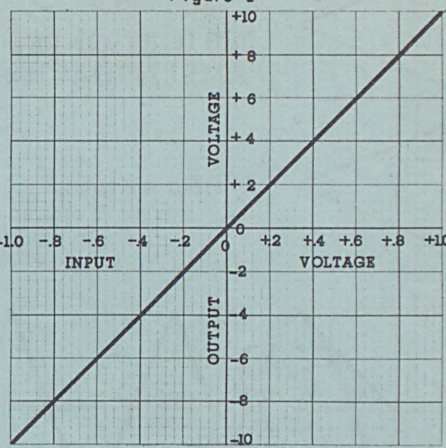


Figure 1

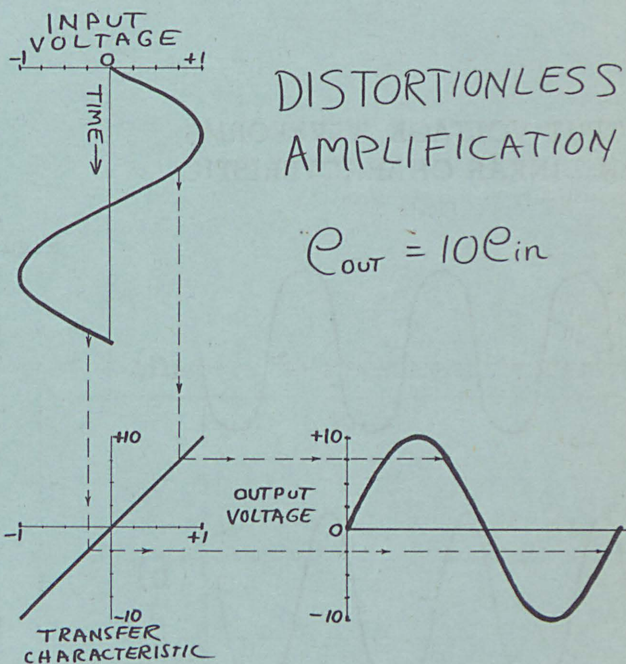


Figure 2

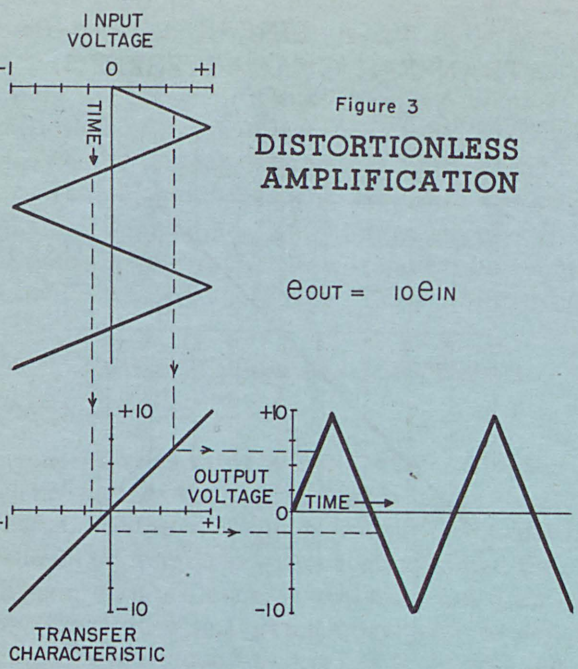
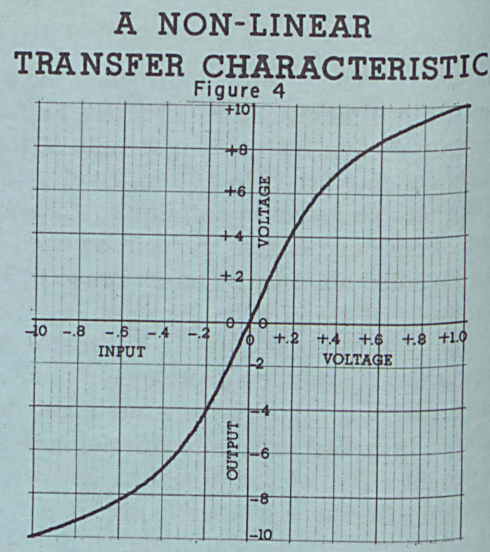


Figure 3



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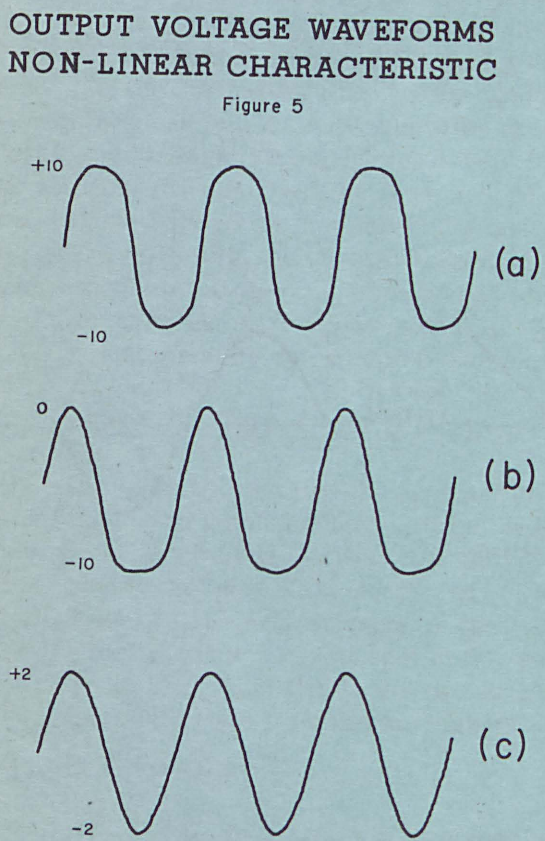
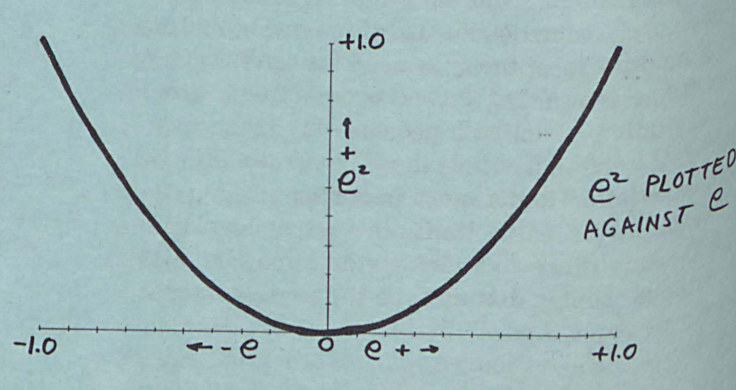
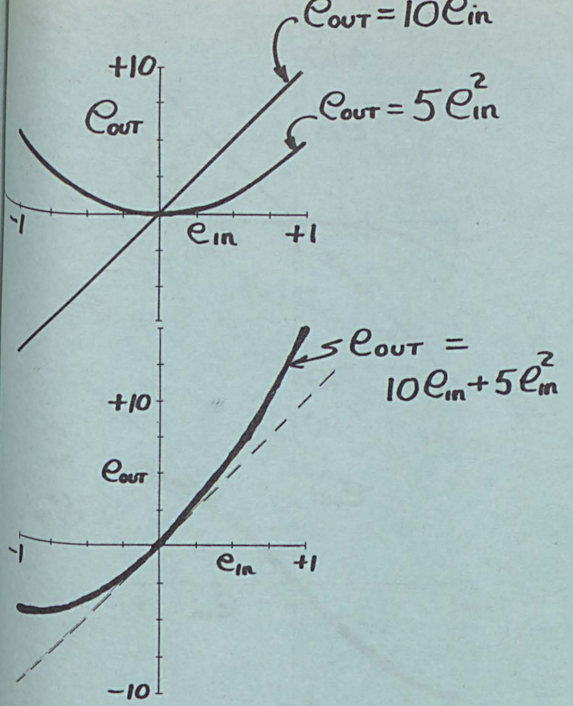


Figure 5

Figure 6





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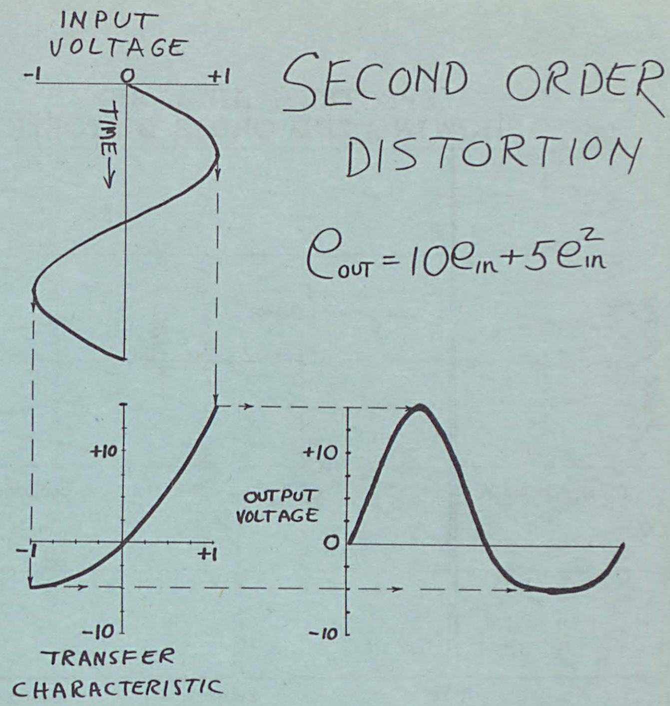

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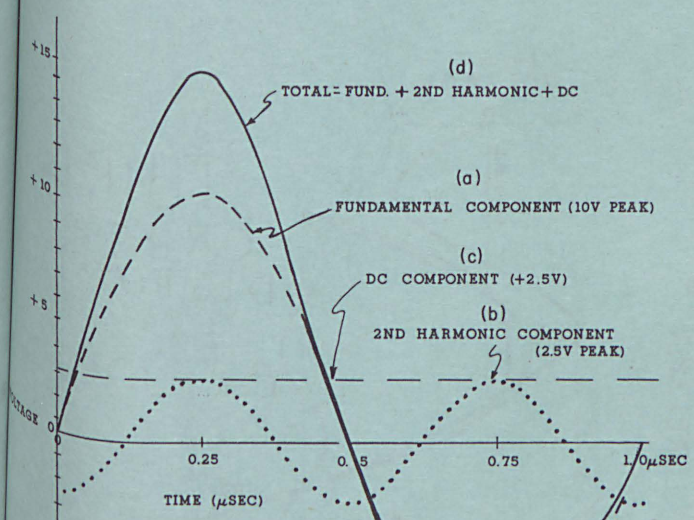

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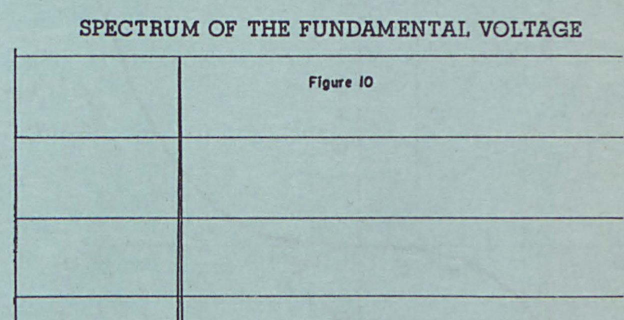

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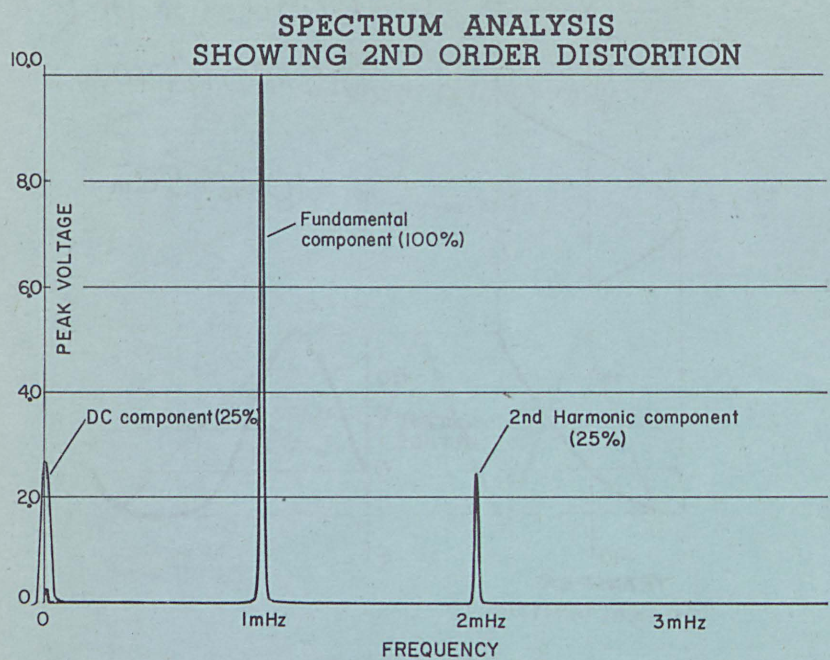

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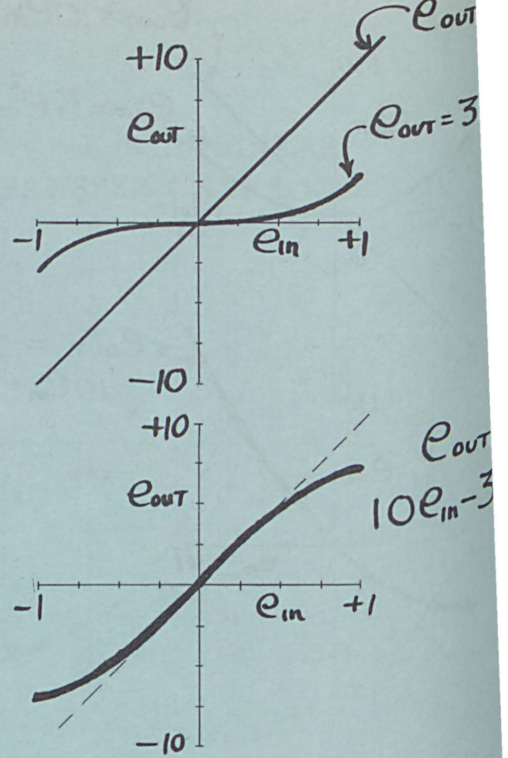
Figure 11



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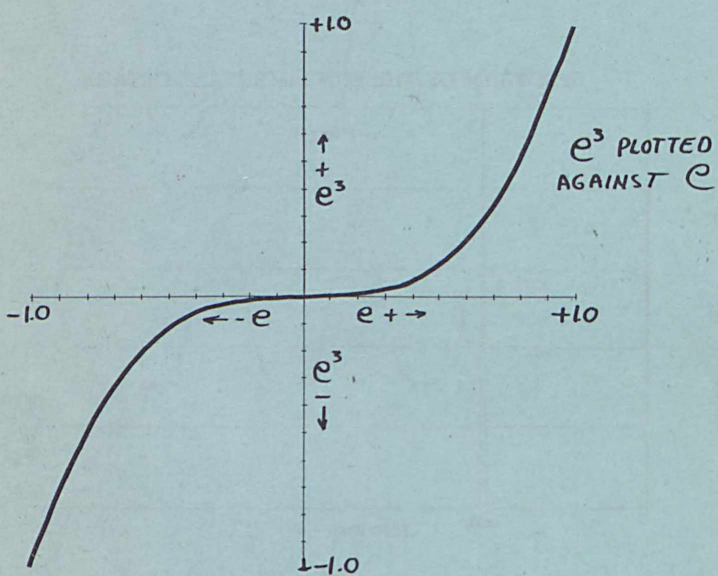

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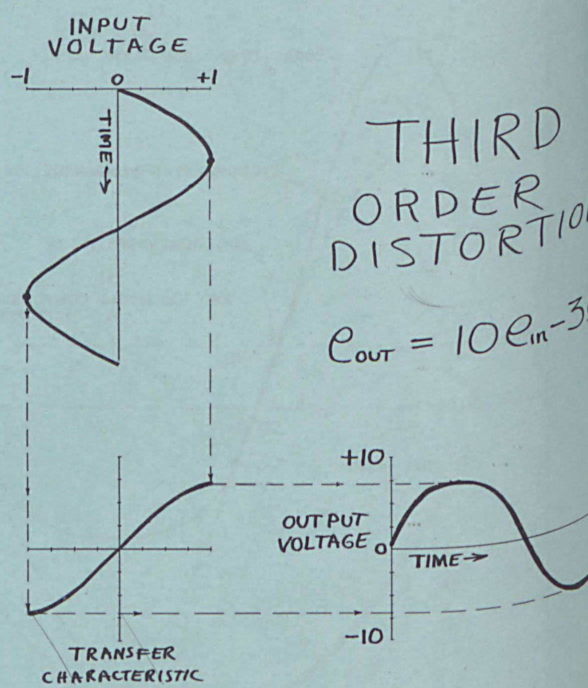
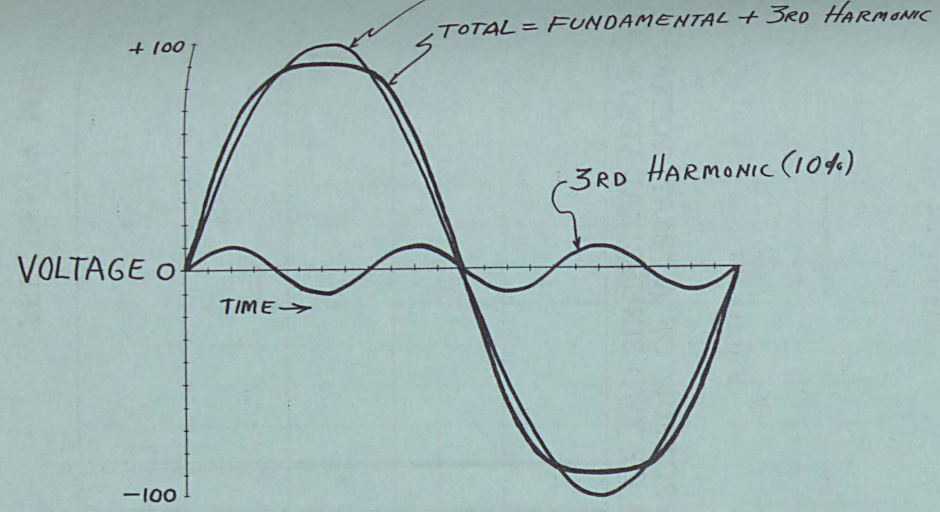


Figure 14

153



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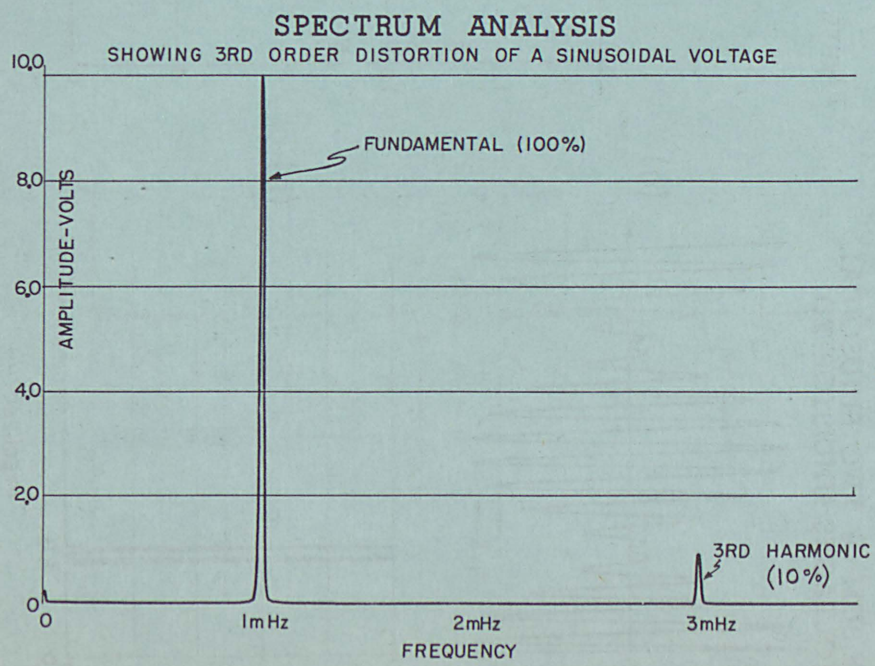


Figure 16

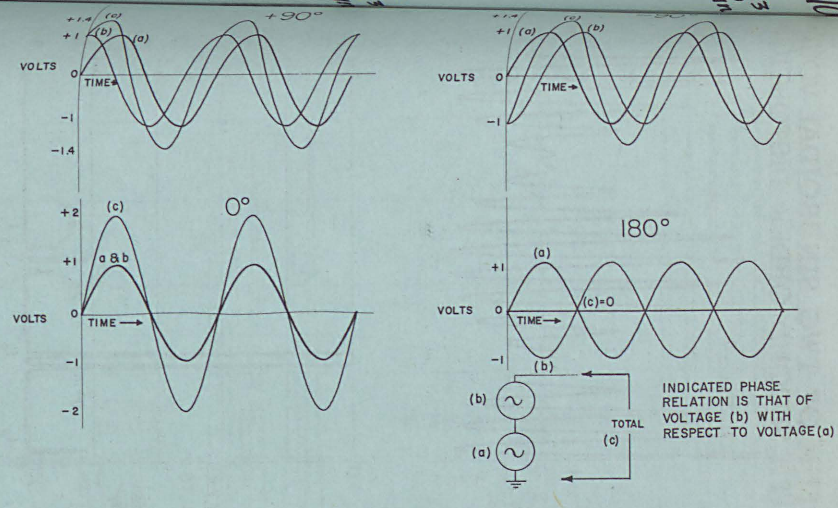
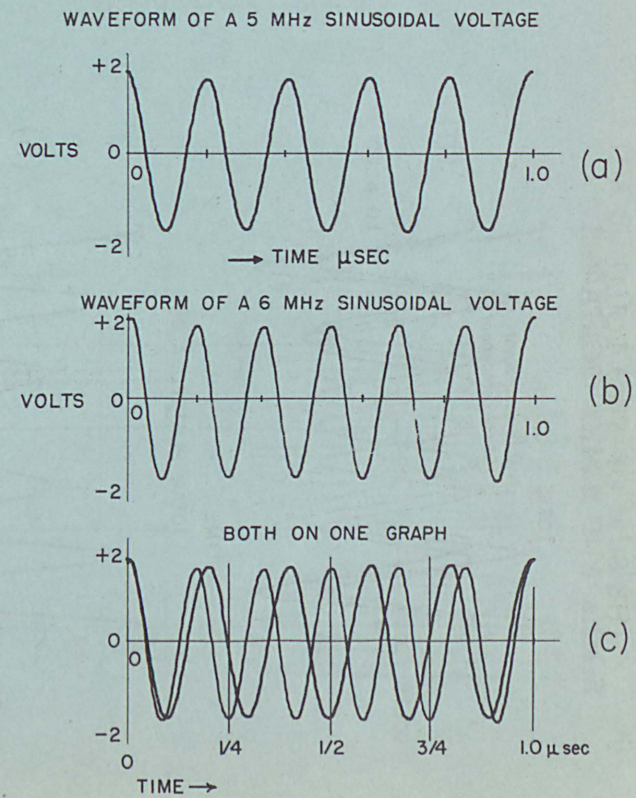


Figure 17



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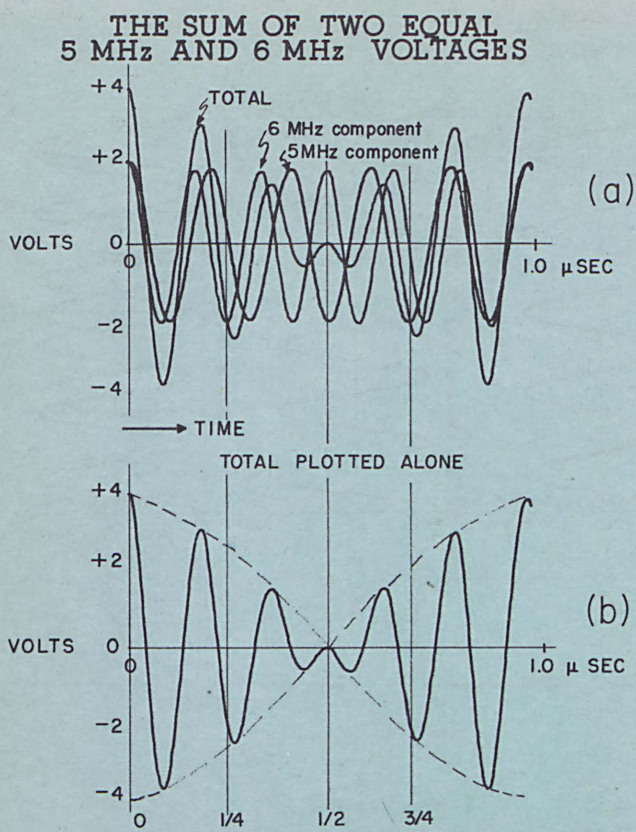

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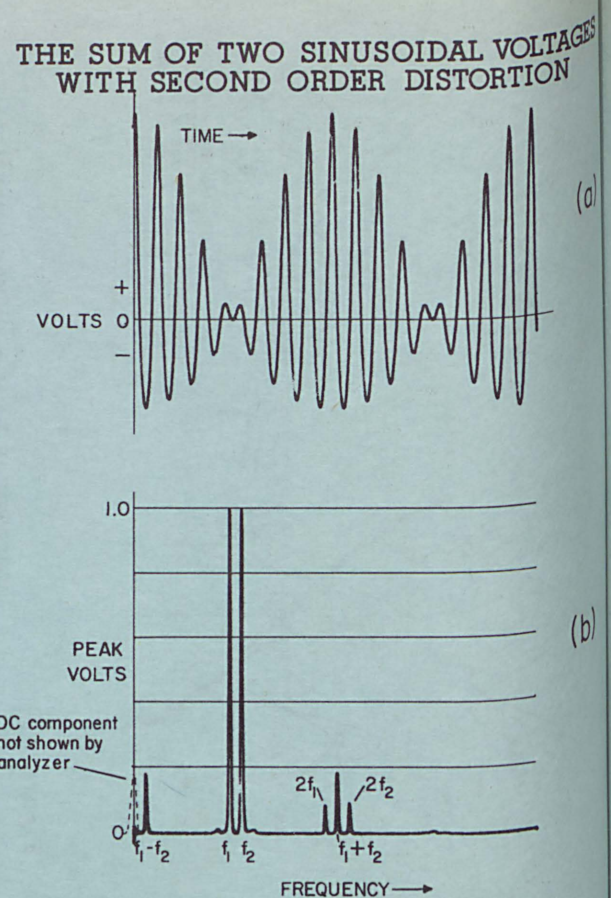


Figure 22

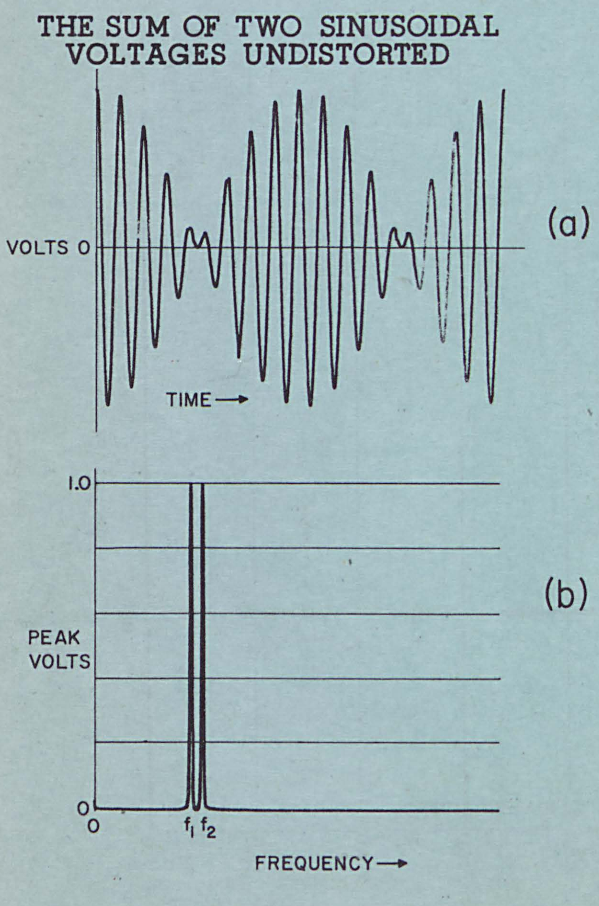
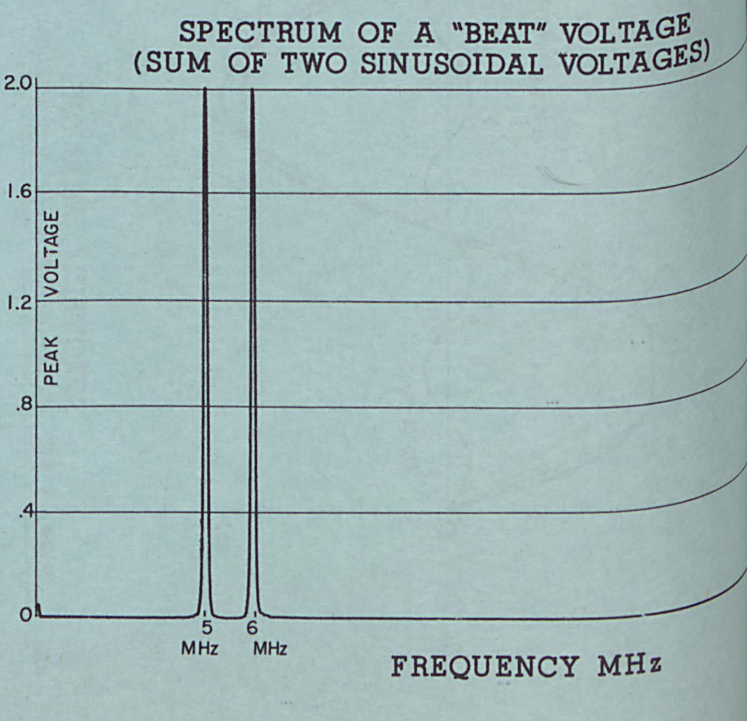


Figure 21

Figure 20



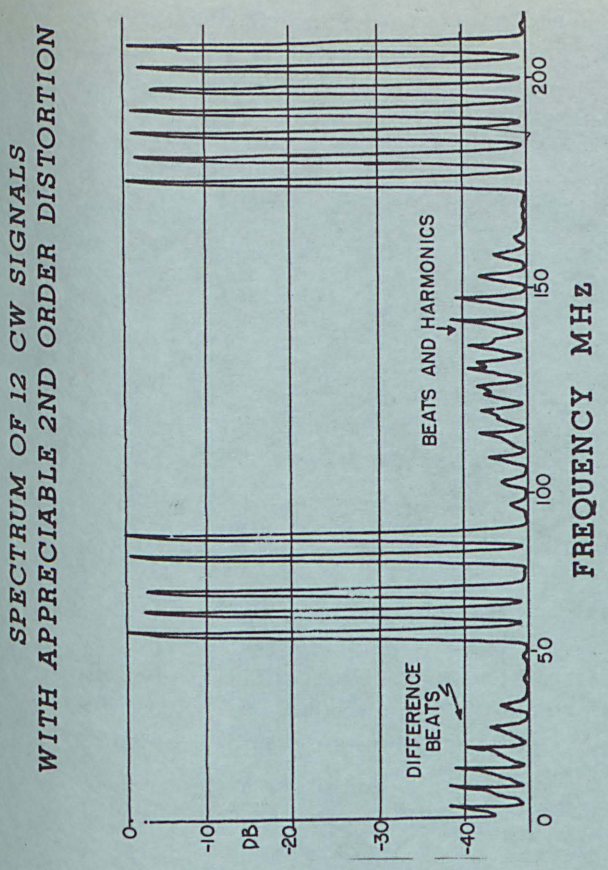


Figure 23

No
Figure
24

THE SUM OF TWO SINUSOIDAL VOLTAGES
WITH THIRD ORDER DISTORTION

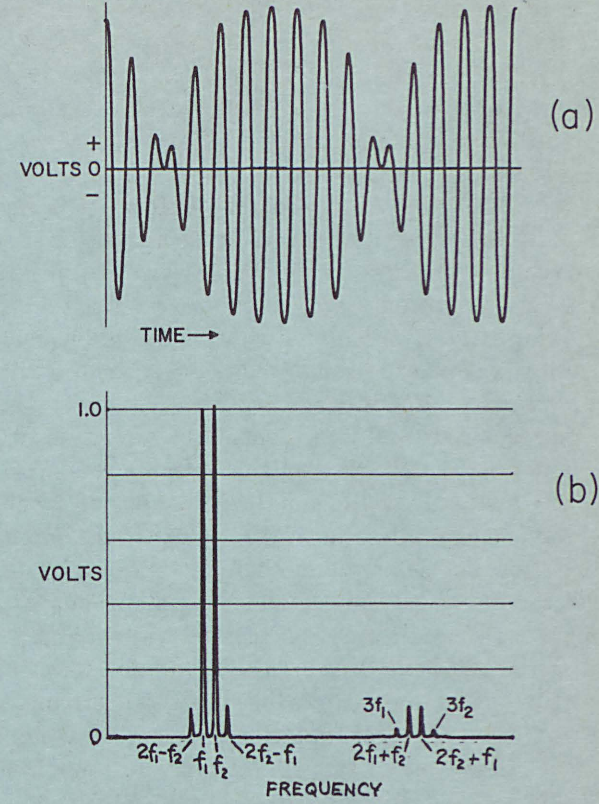


Figure 25

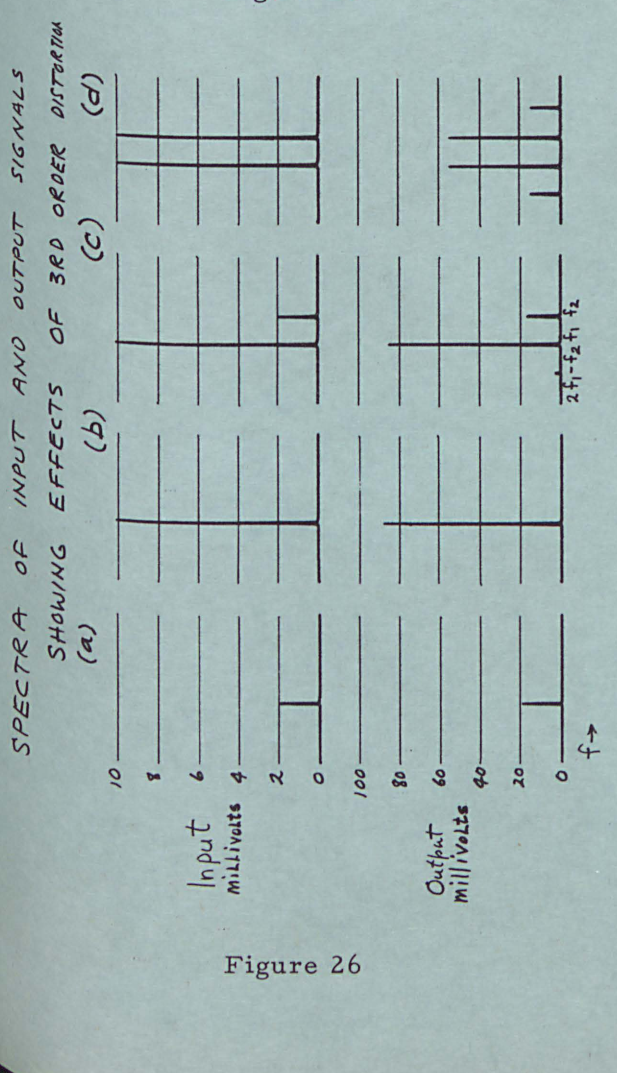


Figure 26

SPECTRUM SHOWING CROSS-MOD

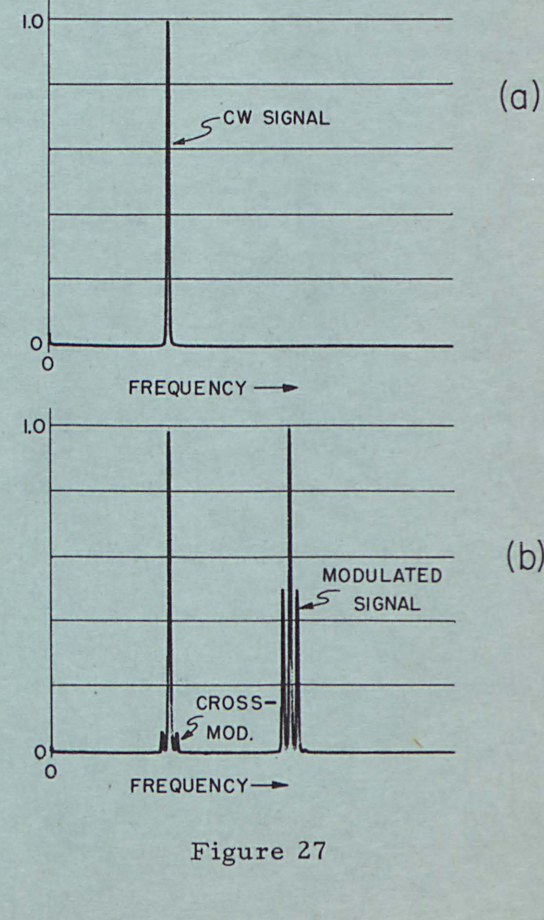


Figure 27

CHAIRMAN TAYLOR: Thank you very much. Does anyone have any questions?

I have a question regarding the effects of cross-modulation on the weaker carriers in a system. If we take a hypothetical case involving one strong carrier and say 8 or 9 weak ones, does the cross-modulation affect all channels equally or is there a difference?

MR. SIMONS: At this point I believe it is necessary to bring out something that was not stressed in my paper. In this presentation I have been talking about "mathematical" amplifiers. By a "mathematical" amplifier, I mean one which follows exactly the same way at all frequencies. With such an amplifier the cross-modulation from all channels on to any one channel would be identically the same.

The unfortunate thing about this approach is it doesn't work. Real-life amplifiers just don't behave this way. Generally speaking, the cross-modulation which shows up on any one channel in an amplifier is not the same as that showing up on any other channel. These differences are not very great so it is still useful to consider the "mathematical" amplifier as an approximation, but the differences are such that we must measure all combinations of channels if we are to be sure of amplifier performance. Generally speaking, there is no difference between weak channels and strong channels, the difference has more to do with the frequency of the particular channel.

CHAIRMAN TAYLOR: Are there any other questions? Thank you very much, Ken. I think it is quite significant in a matter with which I am quite pleased at this convention that we have several systems operators presenting ideas that they have developed in their systems which can be of use to other operators. This is so in the next paper.

Mr. Robert Scherpenseel is the general manager and microwave technician for the Northwest Video of Kalispell, Montana, a system I know a little about. He was chief engineer with WEVR FM of Troy, New York, chief engineer with KBTK radio, and engineer with KMSO-TV electronics technician at Montana State University in installing and maintaining their television and radio and recording systems. Mr. Scherpenseel is going to talk on "A Low Cost TDR". (Applause)

A LOW COST T.D.R.

By

Robert H. Scherpenseel

We are probably being a little facetious in calling this instrument a low cost time domain reflectometer. The 1967 catalogue price is $875.00. In a way it is a TDR but with limitations.

Actually, it is a high quality oscilloscope that has a calibrated time base and a vertical amplifier with a band pass of DC to 10 megaHertz. This is a limiting factor because no determination can be made concerning the frequency characteristics of the information displayed beyond 10 megaHertz.

NEXT SLIDE PLEASE (#2)

This is a picture of the scope with the camera mount in place.

NEXT SLIDE PLEASE (#3)