CASCADING OF INTER-MODULATION DISTORTION IN CABLE TELEVISION SYSTEMS

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INTRODUCTION

Expansion in channel carriage of cable TV systems so that channel allocations appear either between TV channels 6 and 7, or above channel 13, has resulted in new distortion requirements for cable TV systems and amplifiers.

These distortion requirements define the permissible second order distortion in the system and in each amplifier. This is an additional requirement to that of third order distortion. For the latter case, it is already possible to have third order inter-modulation "beats" occur as interfering signals in the standard TV channels. Third order distortion specifications have always been maintained in Cable TV systems rather vigorously to prevent this occurrence. This unique quality of low third order distortion was generated from the specification limitation on cross-modulation distortion; the latter distortion occurring from third order non-linearities. The maintenance of the magnitude of third order interferences to acceptable limits resulted as a by-product of the cross-modulation specification, since if the cross-modulation distortion for 2 channels was down a prescribed magnitude from 100% modulation, then theoretically the triple beat interfering carrier had to also be down from the desired carrier by a related prescribed magnitude. This comparison of the magnitude of third order inter-modulation products and the cross-modulation product has been analyzed and shown by Lotsch[1] and Simons[2]. Before the expansion of cable systems to more than 12 channels, little work had been done in ascertaining or maintaining the magnitude of second order inter-modulation products in Cable TV amplifiers, since the TV channels were originally spaced to preclude second order interfering products from developing. With expansion in the number of channels, attempts were made to use the amplifiers which had exhibited low third order distortion for those new systems in which requirements for second order distortion were severe. The amplifiers performed with varying success, since they had not been originally designed to proper second order distortion specifications.

This then lead to a new generation of amplifiers with improved second order specifications and with new techniques for minimizing the build-up of second order distortions in the CATV trunk cascades.

This paper will examine certain aspects concerning the increase of second order and third order inter-modulation products in CATV amplifier cascades.

A general theory of the manner in which second order distortion cascades in the system will be examined. It will be shown that the magnitude of the cascade effect depends upon the low frequency phase intercept of the phase shift vs. frequency curve of the amplifier. Calculations for several values of the phase intercept will be done to demonstrate the dependence of the second order cascading effect upon the phase intercept. Results of inter-modulation distortion products cascading in CATV systems will be shown as an indication of the manner in which the second order distortion practically cascades, and also as an experimental validation of the theoretical work.

Conclusions will show that second order distortion requirements for Cable TV trunk amplifiers can be fulfilled by state-of-the-art amplifiers, and that amplifiers which operate at higher levels (such as distribution and line extender amplifiers) require a similar magnitude of second distortion levels at their operating levels as those of the trunk amplifier. It will also be shown that in cascaded amplifier systems, third order distortion products cascade in magnitude more rapidly than second order distortions, and are therefore a limiting factor to the length of transmission systems. It will further be stated that the developed theory is applicable to transmission systems other than Cable TV systems.

SYSTEM SPECIFICATIONS FOR INTERFERING CARRIERS

In a Cable TV system, repeater amplifier gain together with cable attenuation is made equal to unity over the complete operating band. For systems of this type, in which the information is carried by amplitude modulation of the carriers, it has been shown that the overload-to-noise ratio of the channels decreases at the rate of 20 log n, where n is the number of amplifiers.[3] This is determined by the increase in noise by 10 log n (power addition) as the signal progresses through the amplifiers, and a required decrease in operating level by 10 log n, since the cross-modulation distortion (which increases by 2dB for each 1dB increase in signal level) increases by 20 log n (voltage addition) as the signal information is cascaded. System specifications for carrier-to-noise ratio, and allowable cross-modulation distortion, are the two most determining factors in defining amplifier appearance for achieving system objectives of Cable TV systems. In other words, repeater amplifier performance in regard to noise figure and cross-modulation distortion are determined by specific system requirements. The object in the repeater amplifier design is to achieve an amplifier which under cascaded type operation will perform in a manner so that system requirements are fulfilled. This amplifier design must achieve its performance at the most economical cost and with a required reliability factor. Over-design of performance factors which add to the manufacturing, installation or maintenance cost, or which degrades the maintainability or reliability of the system should not be considered as a positive factor in the amplifier design. Repeater amplifiers for state-of-art Cable TV systems generally exhibit specifications for noise figure of about 9-10dB and for cross-modulation of about -93dB at operating levels. This is sufficient for achieving cascade operation to system lengths of 1000dB at operating levels of 30-35dBmV. Although improved performance in these areas could be achieved by use of more expensive transistor devices and more expensive techniques (such as paralleling output transistors), the system performance objectives have dictated the amplifier performance, and amplifiers have thus been designed with suitable performance to achieve these objectives with suitable margins.

The criteria for allowable repeater amplifier inter-modulation distortion magnitude should also, therefore, be dictated by system requirements. In order to accomplish this, it is required to define the limits of inter-modulation distortion by the knowledge of the system requirements as to tolerable levels of interfering signals, and the manner in whicn second and third order distortions cascade in a transmission system such as that of Cable TV.

Several investigators have made subjective tests on observations of interferences in TV pictures in order to determine the tolerable level of single frequency interference in a TV picture. The results of these investigations are summarized in Figure 1. Fink considered an in-band carrier interference, such as that of co-channel interference, 55dB down from the video carrier to be a sufficient requirement for limiting interference to a non-observable level. Further work by CATV equipment manufacturers demonstrated that a value of 60dB could be a better requirement for certain worst-case type of situations. Bell Telephone Laboratories considered a worst case of -70dB for peak-to-peak signal vs. RMS interference. The Canadian BP-23 specification dictates a -57dB spec at the horizontal sync frequency and at the color sub-carrier frequency. The value of 60dB has become an acceptable value in the cable TV industry.

This single frequency interference, which is similar to co-channel interference, could result from spurious signals generated from either second or third order, or higher order inter-modulation products. For solid-state linear Class A circuits, such as those of Cable TV amplifiers, the second order distortions are predominate distortion products.

The above mentioned studies have considered only single frequency interferences. To the writer's knowledge, there have been limited and incomplete studies on multi-frequency interferences in TV pictures. Although much work is being done in examining multi-frequency interferences, published results are still sparse. This information is greatly needed since expansion of channel usage to 20 or 30 channels, in which the frequency band is from 50 to 270 MHz (present frequency limits of cable TV amplifiers) results in a multitude of interfering "beats" within each channel.

Evidently, a multitude of operating situations utilizing a multitude of interfering channels will have to be made and be subjectively studied in order to ascertain some criteria for the magnitude of disturbance which can be tolerated. Because of the indeterminate effects of multi-carrier interferences, it is not possible to fully define the tolerable magnitude of interference in a cable system cascade. If only the single frequency interference case is considered, then the figure of -60dB for video carrier to interfering carrier ratio would be an acceptable criteria.

EFFECTS OF AMPLIFIER CASCADING ON INTER-MODULATION DISTORTION

A broadband amplifier, such as the amplifiers used in Cable TV systems, has a linear phase curve within its pass-band. This is a necessary requirement for minimizing differential delay distortions which could otherwise occur. A typical amplifier phase shift curve is shown in Figure 2. An analysis of the variation of inter-modulation products in transmission systems utilizing broadband amplifiers having linear phase shift, has been made by Bell Telephone Laboratories[4]. Results are summarized as follows:

A. Second Order Distortion Components

1. The cascaded second order beat distortion signal A from Amplifier n-1 appears at the output of amplifier n as :

(1) $A_{n-1}(w_1 + w_2) = \cos [(w_1 + w_2) t + \theta_1 + \not{\theta}]$

Where $A_{n-1}(w_1 + w_2)$ is the relative magnitude of the sum frequency of carriers w_1 and w_2 , θ_1 is a fixed phase shift dependent upon the phase shift from one amplifier to the next of the carriers w_1 and w_2 , and $\not{\theta}$ is the extrapolated low frequency phase shift, determined by extending the phase versus frequency curve of the amplifier cable combination along its linear plot down to low frequency. This phase intercept is shown in Figure 2, which is a phase vs frequency plot of a trunk amplifier. It is the intercept at zero frequency of the tangent to the phase curve at any frequency. For an amplifier with linear phase shift, it becomes the extrapolated phase curve to zero frequency.

2. The developed distortion at the output of amplifier number n is

(2) $A_n (w_1 + w_2) = \cos [(w_1 + w_2)t + \theta_1 + 2\phi]$

where the symbols have the same meaning as previously.

B. Third Order Distortion of form $(w_1 + w_2 - w_3)$

1. The cascaded third order distortion signal from previous amplifier appears at the output of the succeeding amplifier as

(3) $A (w_1 + w_2 - w_3) = \cos [(w_1 + w_2 - w_3)t + \theta_2 + \phi]$

where

$A_{n-1} (w_1 + w_2 - w_3)$ is the relative magnitude of the triple beat product of carriers w_1, w_2 and w_3, where θ is a fixed phase shift dependent upon the phase shift from one amplifier to the next of the three carriers, and where ϕ is the zero-frequency intercept described previously.

2. The developed third order distortion at the output of amplifier n is

(4) $A_n (w_1 + w_2 - w_3) = \cos [(w_1 + w_2 - w_3)t + \theta_2 + \phi]$

where the symbols have the same meaning as described previously.

Examination of the second order distortion of equations (1) and (2) indicate that the distortions do not directly add from amplifier to amplifier unless $\phi = 0^{\circ}$. If ϕ is made equal to 180°, a direct cancellation of second order distortion in every other amplifier can occur. For other values of the phase intercept, the result is between total cancellation and total addition.

For the third order distortion case, equations (3) and (4) are shown to be equal, regardless of the value of ϕ (the zero-frequency phase intercept). Therefore, third order distortions of this type will cascade on a voltage addition basis, or as 20 log n, where n is the number of amplifiers in the cascade.

Other forms of second order distortions such as "beats" arising from the different frequencies, and second harmonics and third order distortions, such as those arising from third harmonics, and the sums of three frequencies, could also be studied from a similar analysis as that given in equations (1) through (4).

Analysis shows that the distortions can be summarized by the following:

1. All forms of second order distortions will cascade according to the formula given in equations (1) and (2).
2. Only third order products of the form $w_1 + w_2 - w_3$ and $2w_1 - w_2$ will cascade according to equations (3) and (4).
3. Other forms of third order distortion such as $w_1 + w_2 + w_3$, $3w_1$, and $2w_1 + w_2$ will cascade according to the following:

   Cascaded third order distortion signal from previous amplifiers appears at amplifier n as: (5) $A_{n-1}\ (w_1 + w_2 + w_3) = \cos[(w_1 + w_2 + w_3)t + \theta_3 + \phi]$

   The developed third order distortion at amplifier n is: (6) $A_n\ (w_1 + w_2 + w_3) = \cos[(w_1 + w_2 + w_3)t + \theta + 3\phi]$

It can be seen from equations (5) and (6) that for a specific value of ϕ that the generated distortion at amplifier n can be made out-of-phase with previously generated distortions, so that periodic cancellations of the distortion can be made to occur.

Figure 3 shows polar plots of the relative magnitude and phase of the growth of second order distortions from amplifier to amplifier as a function of the phase of the zero-frequency intercept ϕ. These plots are calculated from summing the distortion contribution from amplifier n-1 and that contributed by amplifier n. The following can be noted from the polar plots:

1. For exactly a zero degree phase shift of the intercept, the distortion increases linearly with the number of amplifiers.
2. For exactly a 180^0 phase intercept, the distortion completely cancels every other amplifier.
3. For phase shifts between 0^0 and 180^0, the distortion magnitude oscillates between a certain limit and the single amplifier value. The distortion magnitude and phase returns to that of the single amplifier value after the number of amplifiers in which $n = \frac{360^0}{\phi^0}$

From this figure, it becomes obvious that if a repeater amplifier and its cable combination could be designed so that the zero frequency intercept is close to 180^0, then the absolute magnitude of the growth of the second order distortion would be not much greater than that from any one amplifier. This is a completely practical situation as will be shown in the succeeding paragraph.

PHASE RESPONSE OF CABLE TV AMPLIFIERS

Figure 4 is a phase vs. frequency plot of the Sylvania trunk amplifier set for flat gain. The phase shift is linear throughout the operating band of 50-270 MHz. If the linear portion of this curve is further extrapolated, as shown by the dotted line of Figure 4, it can be noted that at zero frequency the extrapolated phase shift is 180^0. This is because this particular amplifier has an odd number of stages.

This unique quality of the Sylvania CATV amplifier fulfills the requirement demonstrated in the previous section, that if the repeater amplifier phase intercept is close to 180^{0}, then the second order distortion does not cascade appreciably. However, the flat aligned amplifier is not the actual operating condition of the amplifier. Phase plot in its actual operating condition is also shown in Figure 4. This is with the amplifier aligned for compensation of 23dB of cable, as measured at 270 MHz. It will be noted that the equalization introduces an additional phase shift so that the phase intercept now appears to be closer to 120^{0}. This is still a worthwhile condition, since Figure 3 indicated that a 120^{0} phase intercept results in the cascaded second order distortion still never becoming worse in absolute magnitude then that of any amplifier.

Amplifiers with phase shift type shown in Figure 4 have been used in amplifier cascades in order to test the cascade effects on second order inter-modulation distortion.

CASCADE TESTS FOR SECOND ORDER INTER-MODULATION DISTORTION

Figure 5 shows the results of measurements of a second order inter-modulation "beat" signal after each amplifier in the cascade. This particular beat signal was the sum of channel 5 and channel 6 video carriers. The "beat" frequency was 160.5 MHz. It can be ascertained from Figure 5 that no monotonic increase of the second order distortion occurred in the cascade. Partial cancellation of the distortion appeared to occur after every third amplifier.

Figure 6 is the result of another cascade using channels 4 and 13 as the carriers with the measured distortion being their difference beat. Again periodic cancellation becomes obvious.

Some rise in distortion can be noted. This is due to the fact that amplifier number 9 generated much greater distortion than the previous amplifiers. It, therefore, determined the magnitude of the distortion in the 10-amplifier cascade.

Figure 7 shows results of the cascading of a triple beat. It can be clearly seen that the triple beat cascades, according to theory, at the rate of 20 log n.

Figure 8 shows cascading of a second order distortion sum beat for amplifiers of different types of phase intercepts. For the amplifier with the zero-degree phase intercept, it is obvious that the distortion increases monotonically. With the same amplifier modified so that its phase intercept is 180^{0}, a periodic cancellation occurs.

CONCLUSIONS

It has been shown that second order distortion products in a transmission system can be controlled by judicious choice of the zero frequency intercept of the phase shift curve of the repeater amplifier. Although tests for validating this theory were made for a cable TV system, the theory is fully applicable to any transmission system.

Additional conclusions are:

1. Distribution and extender amplifiers have the same distortion requirements at their higher operating levels as the turnk amplifier, since they appear as additional amplifiers in the cascade. Their zero-frequency phase intercept should also be designed close to 180^{0}.
2. The method of achieving less than the required tolerable maximum of second order distortion for a single repeater amplifier should consider cost, reliability, maintainability, etc. Distortion reduction can be achieved by various means such as proper device

selection and circuit basing, feedback techniques, split-band techniques, proper selection of zero-frequency phase intercept, or by "push-pull" action. Results and performance and not the method should be the governing factors.

3. Certain third order distortions will cascade so as to increase monotonically. For this reason, the third order distortion becomes the predominant factor in limiting the lengths of cable TV cascades.

4. More intensive studies are required by the CATV Industry to more fully ascertain the effects of multi-frequency interferences in expanded channel systems. These studies should be coordinated with consistent criteria so that results can be more readily compared. Among some of the criteria to be defined are:

   a. Exact number of channels.
   b. Exact frequencies, tolerances, and stabilities of all channels.
   c. Levels of all channels.
   d. Effects of changing frequencies and/or levels of certain channels.
   e. Conditions of TV viewing.

   Results should then be noted on each and every channel.

Acknowledgement is given to Mr. Timothy Eller and Marty Zelenz of GTE Sylvania CATV Operations for their assistance in validating some of the analysis and in providing some of the test data.

REFERENCES

1. H.K.V. Lotsch — "Theory of Nonlinear Distortion Produced In A Semiconductor Diode"; IEEE Transactions on Electron Devices, May 1968, pp. 294-307.

2. Ken Simons — Technical Handbook for CATV Systems; Third Edition, March 1968.

3. William A. Rheinfelder — CATV System Engineering; Second Edition.

4. Bell Telephone Laboratories — Transmission Systems for Communications; pp. 224-228, Revised Third Edition.

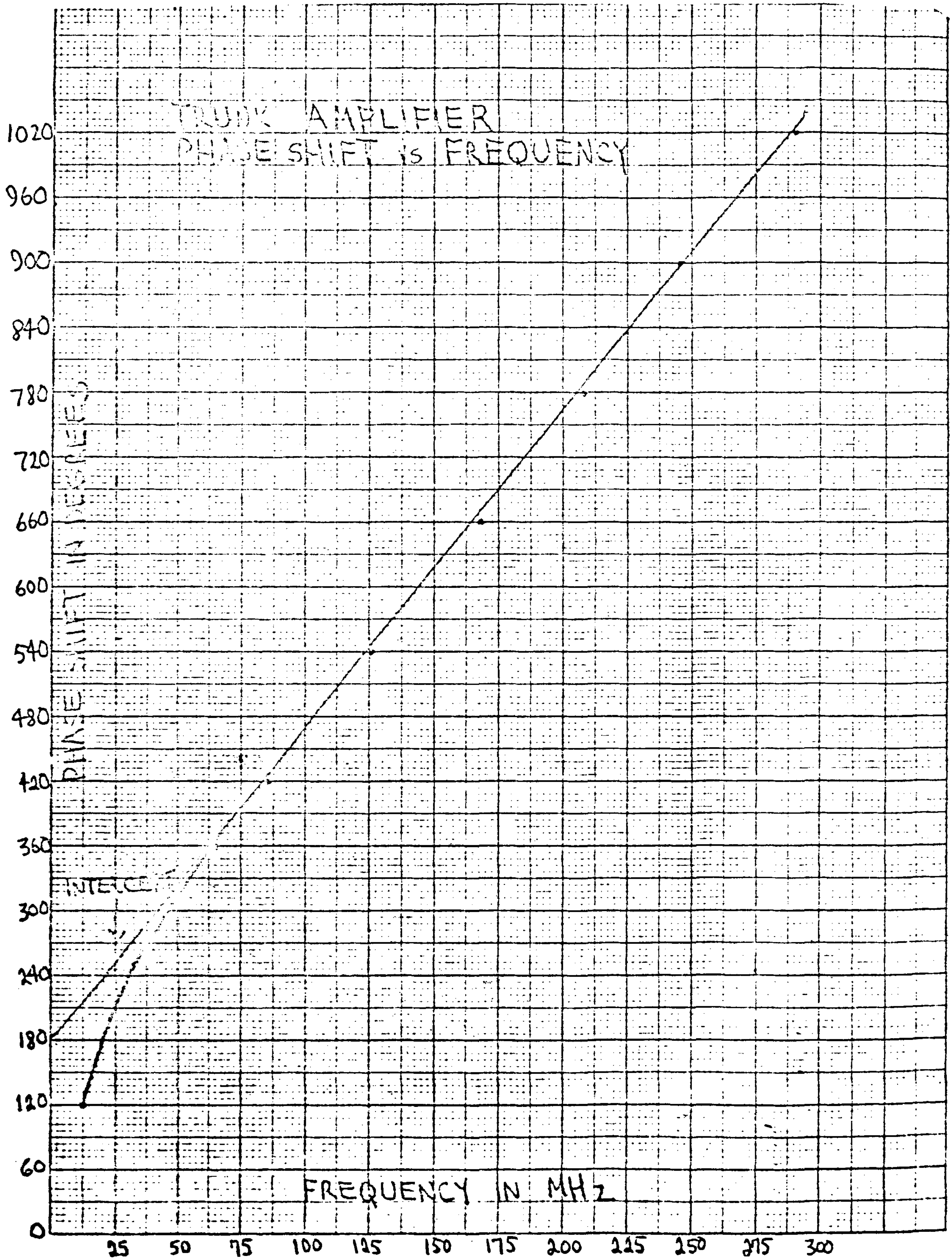
Figure 1

SINGLE FREQUENCY

IN-BAND INTERFERENCE TOLERANCE

INVESTIGATOR	SPECIFICATION
FINK-TELEVISION ENGINEERING	-55dB
CANADIAN-TELEVISION STANDARD BP-23	-57dB AT SYNC FREQUENCY AND AT COLOR SUB-CARRIER
ACCEPTED INDUSTRY STANDARD	-60dB WORST CASE
BELL LABORATORIES	-70dB AT SYNC FREQUENCY RMS INTERFERENCE TO P-P SIGNAL

Figure 2


TRUNK AMPLIFIER
PHASE SHIFT vs FREQUENCY
PHASE SHIFT IN DEGREES
FREQUENCY IN MHz
INTERCEPT
1020
960
900
840
780
720
660
600
540
480
420
360
300
240
180
120
60
0
25
50
75
100
125
150
175
200
225
250
275
300

2ND ORDER DISTORTION INCREASE AS FUNCTION OF PHASE INTERCEPT

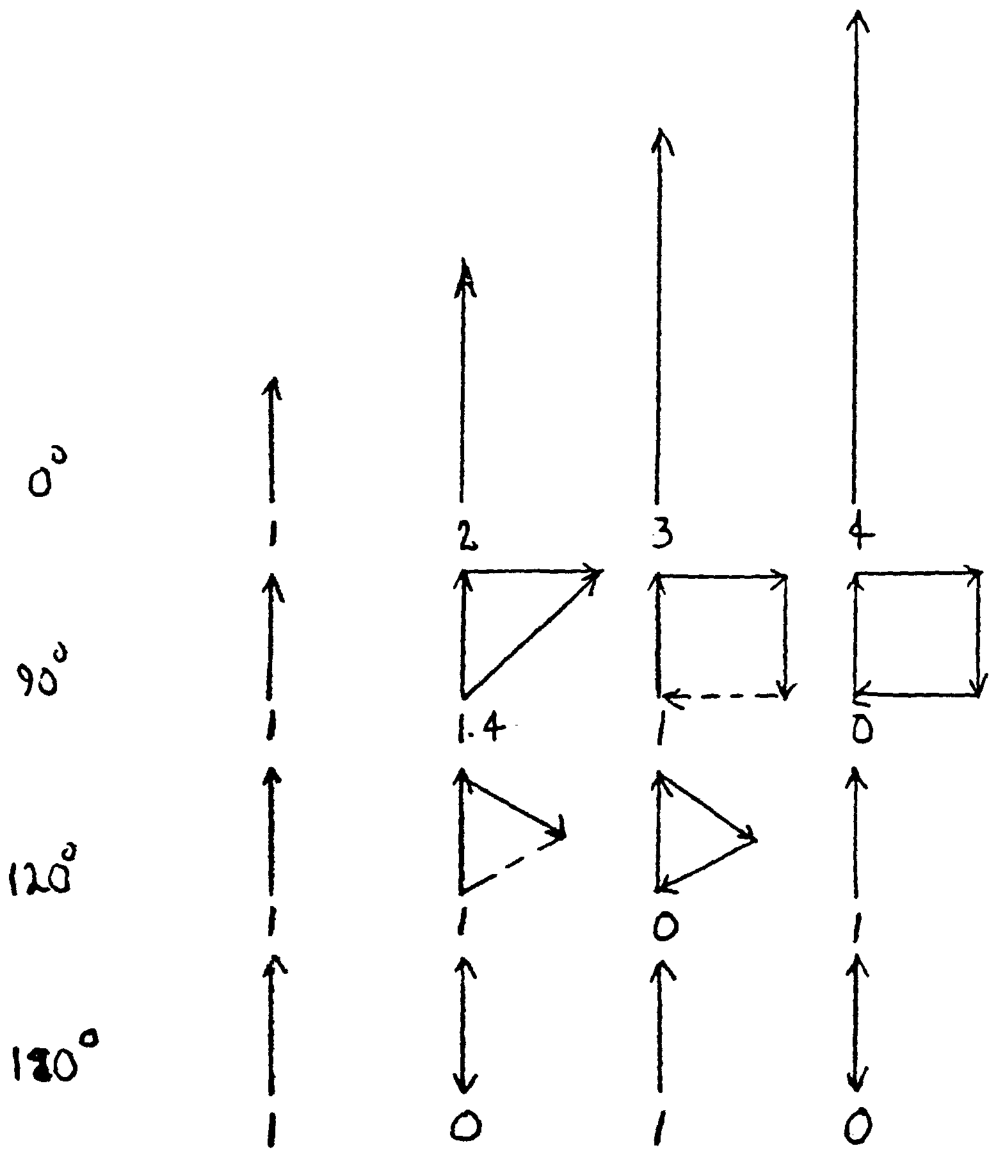
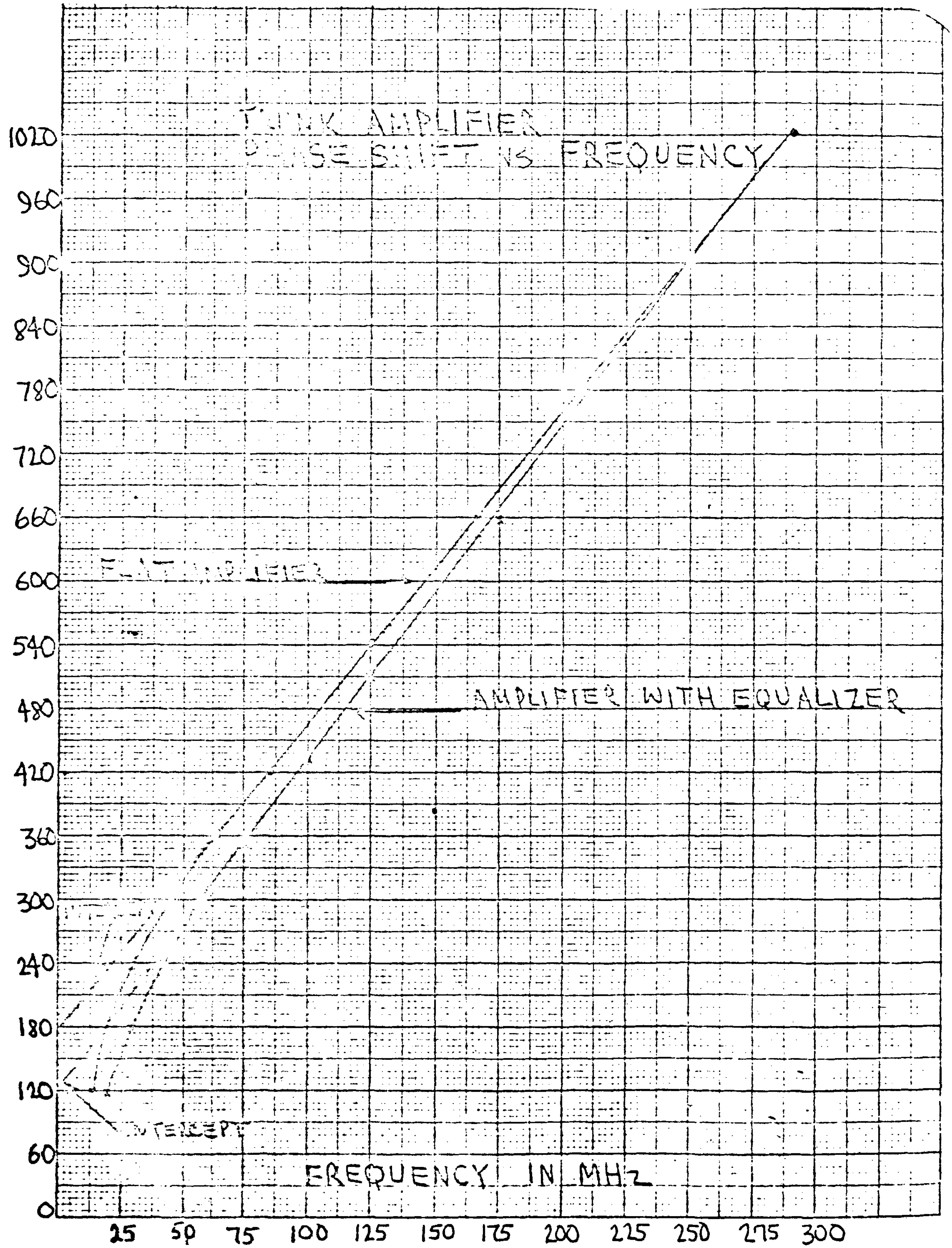


Figure 4



TRUNK AMPLIFIER
PHASE SHIFT VS FREQUENCY
FLAT AMPLIFIER
AMPLIFIER WITH EQUALIZER
INTERCEPT
FREQUENCY IN MHz
1020
960
900
840
780
720
660
600
540
480
420
360
300
240
180
120
60
0
25
50
75
100
125
150
175
200
225
250
275
300

Figure 5

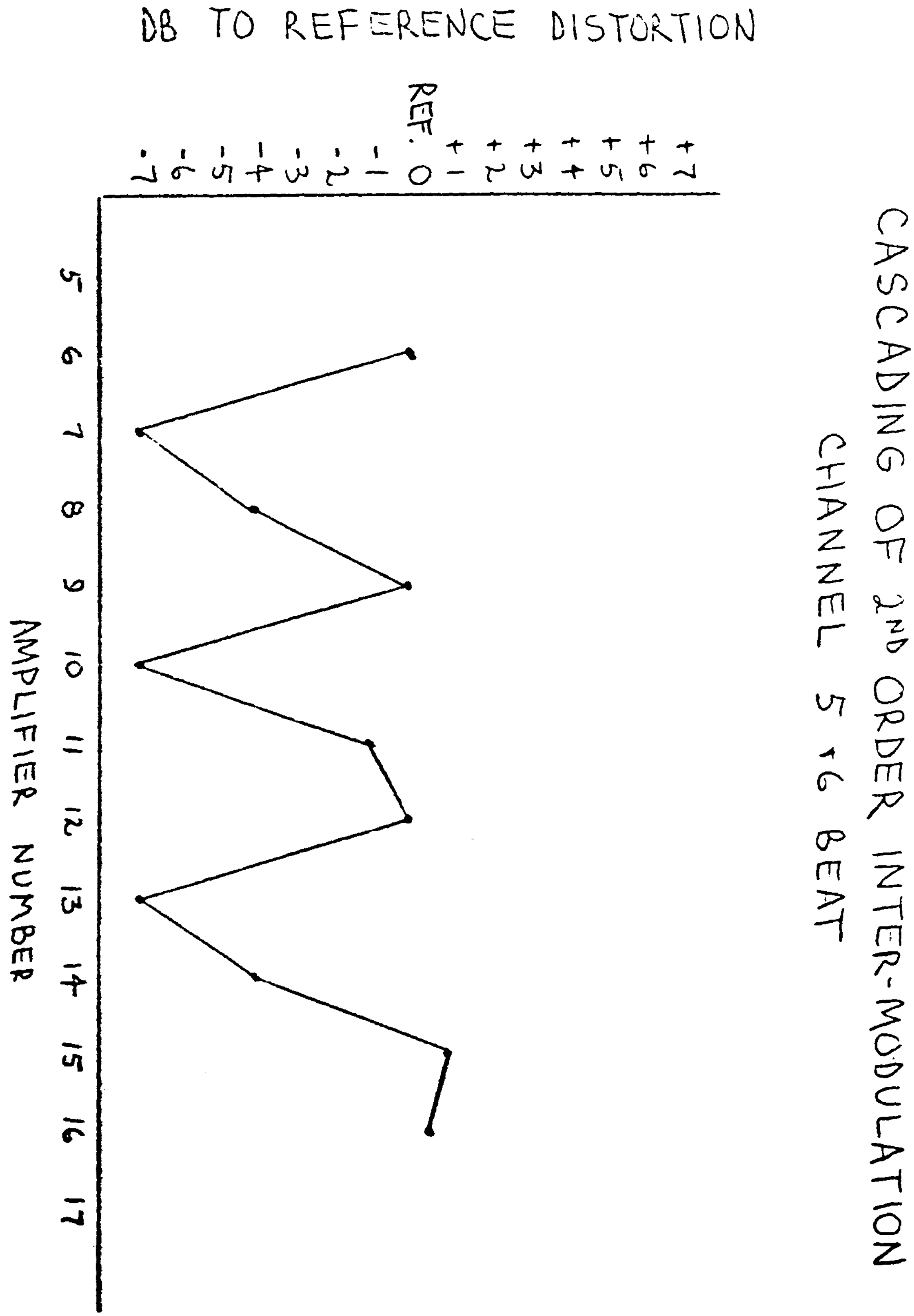

CASCADING OF 2ND ORDER INTER-MODULATION
CHANNEL 5 + 6 BEAT
DB TO REFERENCE DISTORTION
REF.
-7 -6 -5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5 +6 +7
AMPLIFIER NUMBER
5 6 7 8 9 10 11 12 13 14 15 16 17

Figure 6

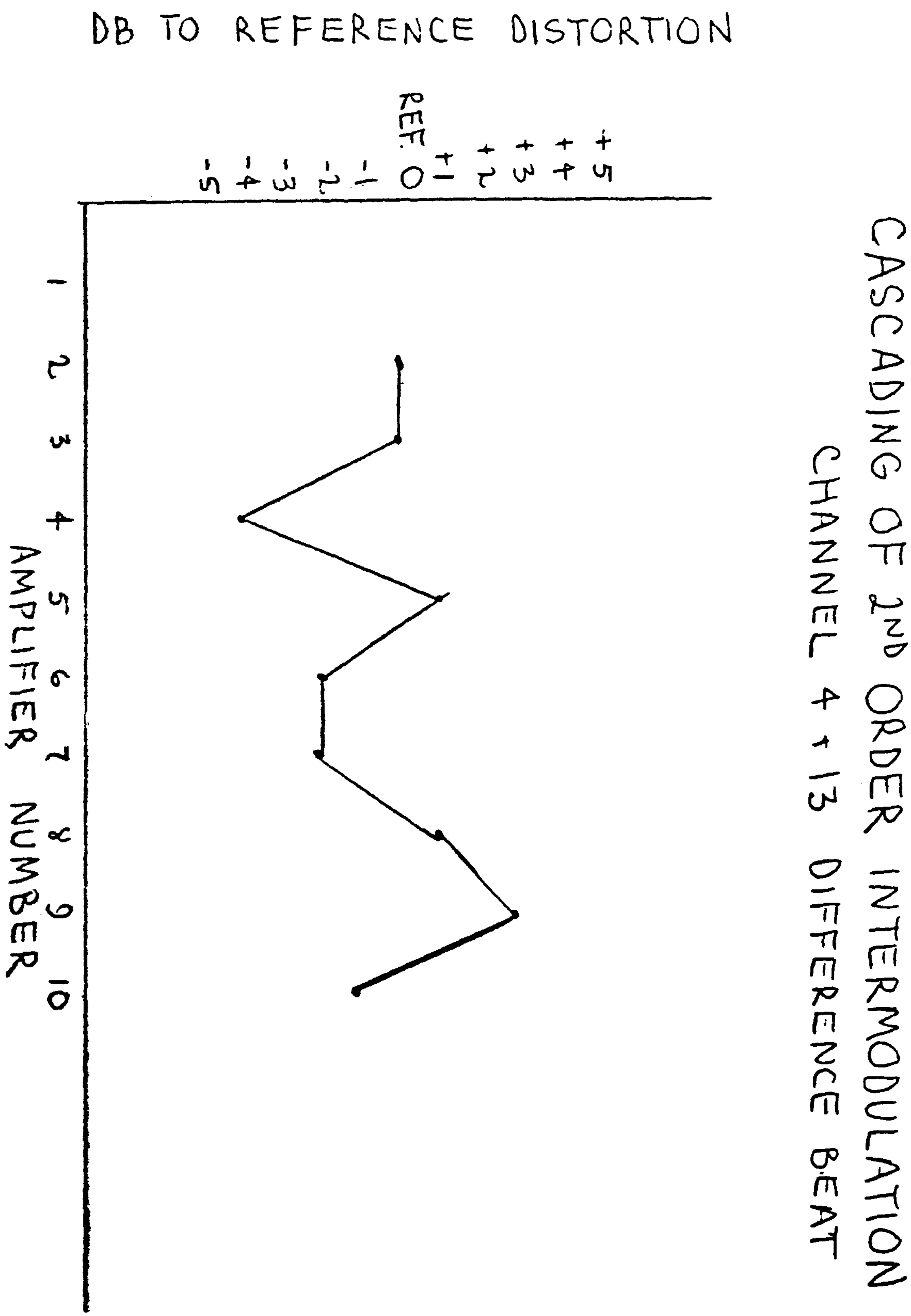
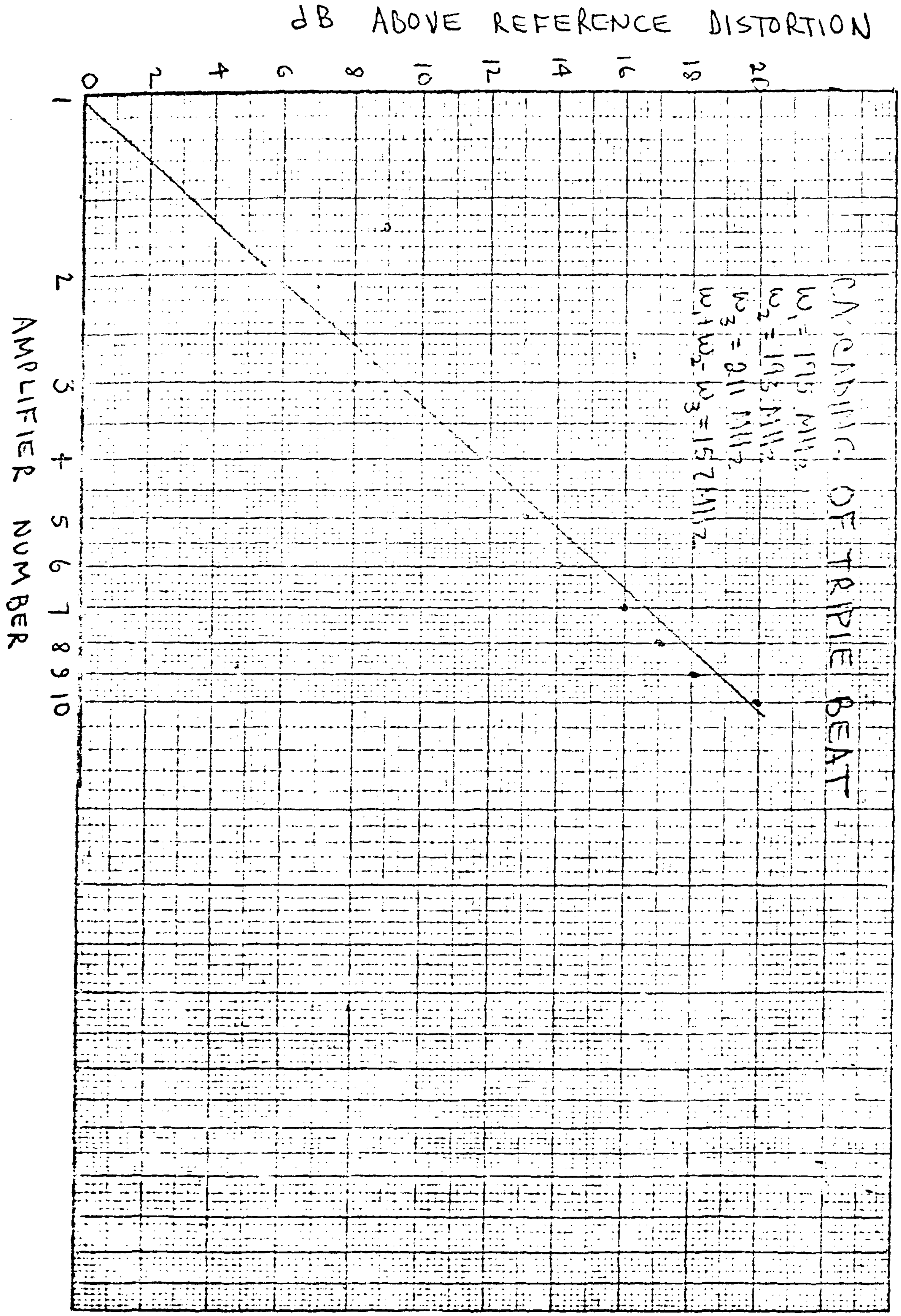

CASCADING OF 2ND ORDER INTERMODULATION
CHANNEL 4 + 13 DIFFERENCE BEAT
DB TO REFERENCE DISTORTION
+5
+4
+3
+2
+1
REF. 0
-1
-2
-3
-4
-5
AMPLIFIER NUMBER
1
2
3
4
5
6
7
8
9
10

Figure 7


dB ABOVE REFERENCE DISTORTION
0 2 4 6 8 10 12 14 16 18 20
AMPLIFIER NUMBER
1 2 3 4 5 6 7 8 9 10
CASCADING OF TRIPLE BEAT
ω1 = 175 MHz
ω2 = 193 MHz
ω3 = 211 MHz
ω1+ω2−ω3 = 157 MHz

CASCADING OF DISTORTION
IN 3 AMPLIFIER CASCADE
CHANNEL 5+6 BEAT