DISTORTION MEASUREMENT TECHNIQUES FOR CATV

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In this discussion, distortion will be limited to the effect called "windshield wiper" distortion. Harmonic distortion, spurious frequencies, noise, hum and other forms of distortion will not be considered here.

I Windshield Wiper Effect and Rf-Distortion

In multi-channel TV systems the maximum practical signal level or overload level is usually determined by the onset of windshield wiper distortion. In windshield wiper effect, the sync pulses of one or more undesired TV signals appear as superimposed modulation upon the modulation of the desired carrier. Since sync pulses of different TV stations are of very closely the same frequency, but are not synchronized, vertical or diagonal bars appear which seem to drift from side to side at a low audio rate determined by the difference frequency of the respective sync pulses.

Modulation of an undesired carrier being impressed upon the desired signal is by definition cross modulation. Unfortunately, windshield wiper distortion is a much more complicated effect and can only under special circumstances be directly related to measured cross modulation. To get a better understanding of windshield wiper distortion, we consider first standard cross and intermodulation distortion[1].

Distortion causing nonlinearities can generally be expressed by a power series of the form

$$e_o = a_o + a_1 e_i + a_2 e_i^2 + a_3 e_i^3 + \dots \qquad (1)$$

where e_o = output voltage
e_i = input voltage
a_n = coefficient of power term n

We substitute for the input voltage the sum of the modulated desired signal and a modulated undesired signal, or

$$e_i = e_d \cos \omega_d t \,(1 + m_d \cos p_d t) + e_u \cos \omega_u t \,(1 + m_u \cos p_u t) \qquad (2)$$

where e = peak voltage of carrier
ω = frequency of carrier in radians
m = modulation index of carrier
p = modulation frequency of carrier in radians
d = desired (subscript)
u = undesired (subscript)

After short calculation, we find that modulation of the desired carrier by the undesired carrier can be produced only by third or higher order distortion. To obtain cross modulation distortion, term a_3 in equ. (1) must exist. The cross modulation factor is then found as

$$k_c = 3\, a_3\, m_u\, e_u{}^2 \,/\, a_1\, m_d\,, \qquad (3)$$

with the parameters as defined above.

Second order distortion, expressed by the term with coefficient a_2 in (1), does not produce cross modulation, but does result in first and second order sum and difference frequencies, which are called intermodulation products and are the cause of what is termed spurious frequencies. Generally, inter-modulation frequencies are defined by

$$f = nf_1 \pm mf_2 \qquad (4)$$

where f = intermodulation frequency
f_1 , f_2 = interfering frequencies
n , m = integer numbers

By substituting expression (2) into (1), intermodulation factor is found as

$$k_i = a_2\, e_u / a_1 \qquad (\omega_d \pm \omega_u) \qquad (5)$$

and for second order products

$$k_i' = 3\, a_3\, e_d\, e_u \,/\, 4a_1 \qquad (2\,\omega_d \pm \omega_u\, ;\, 2\,\omega_u \pm \omega_d) \qquad (5a)$$

The theory of active devices shows that by certain circuit design techniques the term a_3 in (1) may be nulled, while term a_2 can normally only be minimized. Tests were already conducted in 1960 to obtain a correlation between observed windshield wiper distortion and cross modulation. All results were negative. Selected transistors, as well as specially designed semiconductors with cross modulation products reduced by 30 db as compared to normal samples, showed no improvement in windshield wiper distortion and in some cases resulted in even increased windshield wiper effect. A correlation to intermodulation was attempted, also with poor results. Windshield wiper distortion, therefore, represents a far more complex effect than simple cross modulation or intermodulation.

Specialized test equipment was then designed[2] to shed further light on the exact mechanism of windshield wiper distortion. Such equipment is necessary if we consider the normal test procedure for windshield wiper effect and its inherent sources of error which preclude any research effort. Before proceeding any further, it is necessary to re-examine this direct test method in detail.

II The Direct Method and Its Error Sources

In normal windshield wiper testing of CATV amplifiers[3], twelve TV signals are applied to the input of an amplifier and the level is increased until windshield wiping is noticed as monitored on a TV set connected to the output of the amplifier. This level is often termed the overload level of the amplifier. While this test procedure is awkward and loaded with errors, it is by no means obsolete. It must still be referred to as the ultimate performance criterion until a better and repeatable distortion measurement technique has become available and a distortion percentage number has been agreed upon by correlation to a certain picture degradation in the normal test procedure. This is analogous to a visual test as the ultimate criterion for signal to noise ratio until the time that a number could be agreed upon, such as 40 db video signal to noise ratio for a studio quality picture. There is then a two-fold problem in developing any standard test method:

1) The development of a repeatable and accurate test technique which directly correlates to an actual observed effect.
2) The agreement upon a number to correlate to a certain acceptable quality level.

Point 2 reaches very much into subjective factors and again cannot be undertaken until a repeatable test technique exists (point 1). Until both points are fully covered, the direct test method must still be considered the ultimate performance criterion.

With this in mind, let us consider the various error sources of the direct method and their elimination. As mentioned above, in the direct method, TV signals are applied to the amplifier under test and windshield wiper distortion is directly observed in the output on a TV screen. This test method does, of course, closely resemble the actual conditions encountered in a CATV system; however, the error sources for testing amplifiers are numerous:

1) Errors due to conversion and sync correlation

In order to obtain twelve-channel signals, all local signals are usually used directly for testing and any empty channels are filled by frequency conversion of the same local signals. This process in itself leads to a different signal quality for the converted signal and a possibility of errors. For example, in the conversion process sync pulses might be compressed, which then results in a lower reading of distortion than is actually present.

The derivation and assignment of the signals for the empty TV channels is even more important. No windshield wiping is possible if all test signals are derived from a common sync, that is one TV signal. Since the number of local stations is usually limited, it will be necessary to use the same off-the-air signal several times. It is important to avoid a conversion scheme where adjacent channels result with correlated sync pulses. For example, if Channels 11 and 13 are available off-the-air, these signals should not be used to produce by conversion a Channel 12 signal, since then adjacent channels use the same sync pulses and windshield wiping is not possible. A lower reading than the actual distortion will be obtained.

2) Errors due to live signals

Modulation levels of live signals are inconsistent. Sync pulses are often poorly shaped and transmitted as such over the air; occasionally inverted sync pulses dipping into the video signal are obtained. Carrier levels often fluctuate several dB. All of these cases lead to proportional measurement errors leading to poor repeatability. Also, the video signal itself tends to mask some forms of distortion.

3) Spurious responses

Interference beats of a variable nature often occur when using live signals. Such beats mask windshield wiper effect. Since their intensity often varies with time, they introduce a measurement error due to a change in distortion visibility.

4) Level errors

The signals applied to the amplifier under test must have the specified levels. Also, output level must be read accurately. Any level errors due to rf-voltmeter inaccuracy or other instrumentation problems appear directly in the reading. This includes level errors of those field strength meters which are affected by varying modulation depths of a TV signal.

5) Errors in TV screen read-out

Normal TV-receivers are not designed for adjacent channel reception. Most sets show windshield wiping at a level of about +10 dbmv. By adjusting the fine tuning, adjacent channel windshield wiping can be improved; however, this results in a misadjustment of the receiver. Consequently, the level to the TV set must be kept always at a safe input level by a separate attenuator; preferably the input level to the TV set is kept constant regardless of the level applied to the amplifier under test. As was mentioned, fine tuning does drastically change the visibility of windshield wiper distortion, as does the setting of contrast and brightness controls. Contrast and brightness should be set for good whites and blacks visible simultaneously, fine tuning to the point of diappearance of sound bars. All of these sources of errors again add several dB to the total inaccuracy. Lastly, the subjective factor of the observer must be considered. As has been demonstrated, there is another margin of several dB between what may be visible to one person as compared to another individual.

There are several other error sources which relate more to the practical aspects (discussed below). However crude the direct method is, it must still be resorted to as the final criterion in case of doubt until another measurement method has been developed whose direct correlation to windshield wiper effect has been fully established.

As an improvement to the basic direct method, a reference amplifier is often used which has a known distortion level. This amplifier is measured before each distortion test and a correction is then made to all readings accordingly. In this fashion, errors due to a varying off-the-air condition, drifts in instruments, errors in adjustments of the TV set, etc., may be largely eliminated and much more consistent and repeatable readings are obtained, although the absolute level of distortion is still in doubt.

III Problems in Correlating Observed Windshield Wiper Effect to Measured Data

As was mentioned in Section I, measurements have proven conclusively that there is no direct relationship of observable windshield wiper effect to either cross or intermodulation. For a deeper understanding of the exact mechanism we must consider the results of a more detailed study of windshield wiper effect which was performed using specially designed test equipment. If windshield wiping were caused by pure cross modulation (3rd order nonlinearities only) black bars should appear since sync pulses are in the infra-black region. These black bars are indeed observable with special test equipment and they can be measured and behave very much like standard cross modulation. Unfortunately, they do not represent windshield wiper effect to the average viewer since they remain generally invisible. As level is increased, distortion increases, however, with a gradual phase reversal. Black bars change gradually from black to gray and then to white. As the shading changes, the bars become invisible since they blend with the background intensity of the screen. We have here a case where visible distortion decreases, although measured distortion increases. Finally, with a further increase in level the bars become white and we have the condition normally understood as windshield wiper effect. At this point distortion increases rapidly and becomes noticeable and objectionable to the subscriber in a CATV system. The difference between the onset of windshield wiping visible to a critical, trained observer and being objectionable to the average subscriber is usually not more than 4 db. The change in visibility of distortion is depicted in Figure 1. The peak visibility level in "black wipe" is typically 15 to 20 dB below the level for the onset of windshield wiping and its magnitude is normally too low to be visible except with special test set-ups. Only in some rare cases of drastically incorrect circuit design, can "black wipe" actually be the cause of objectionable windshield wiper effect and can be distinguished as such by an experienced observer. The generation of "black wipe" is well understood and follows expression (3), Section I. "White wipe," which is the distortion of main interest in CATV, is generated by a different mechanism and is not explained by the direct action of cross or intermodulation or higher order nonlinearities (see Appendix I).

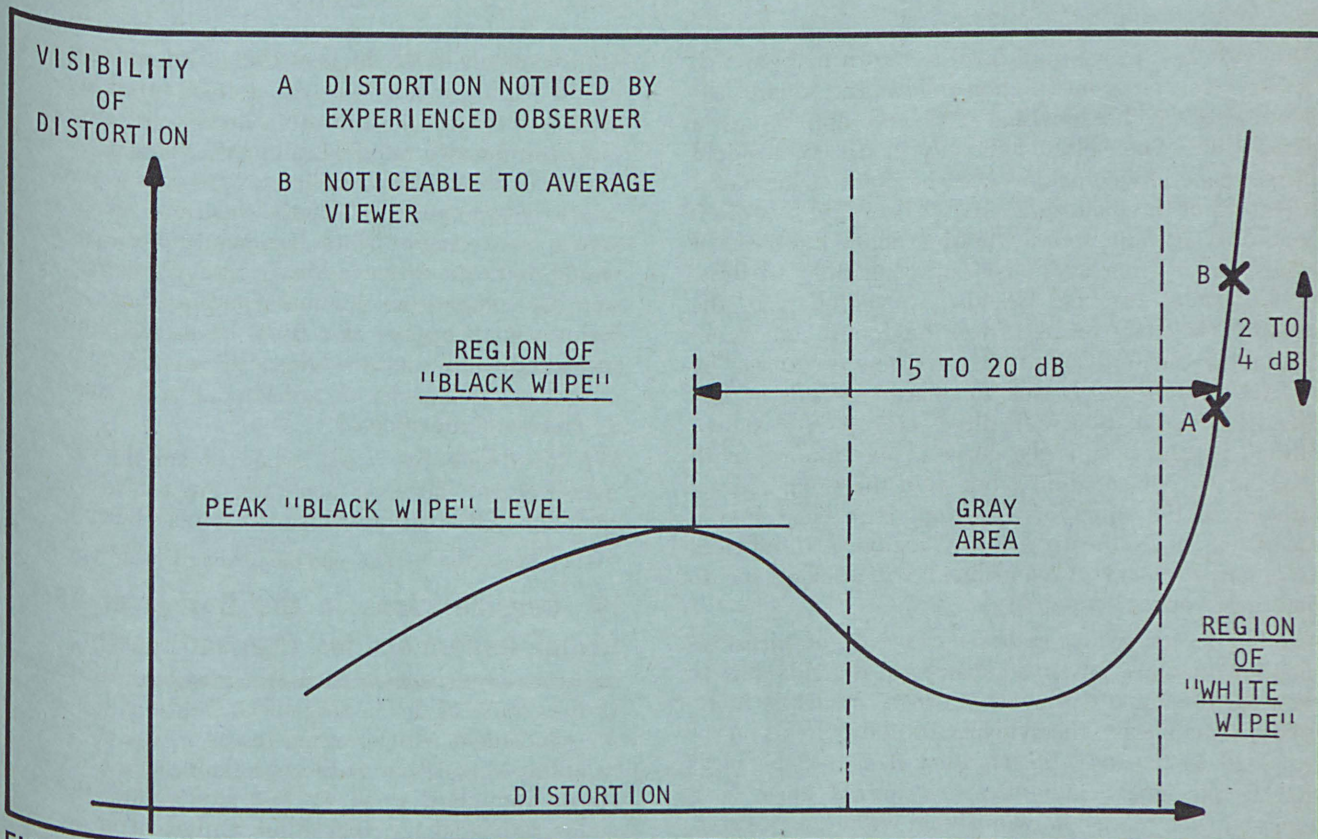

FIGURE 1 VISIBILITY OF WINDSHIELD WIPER EFFECT

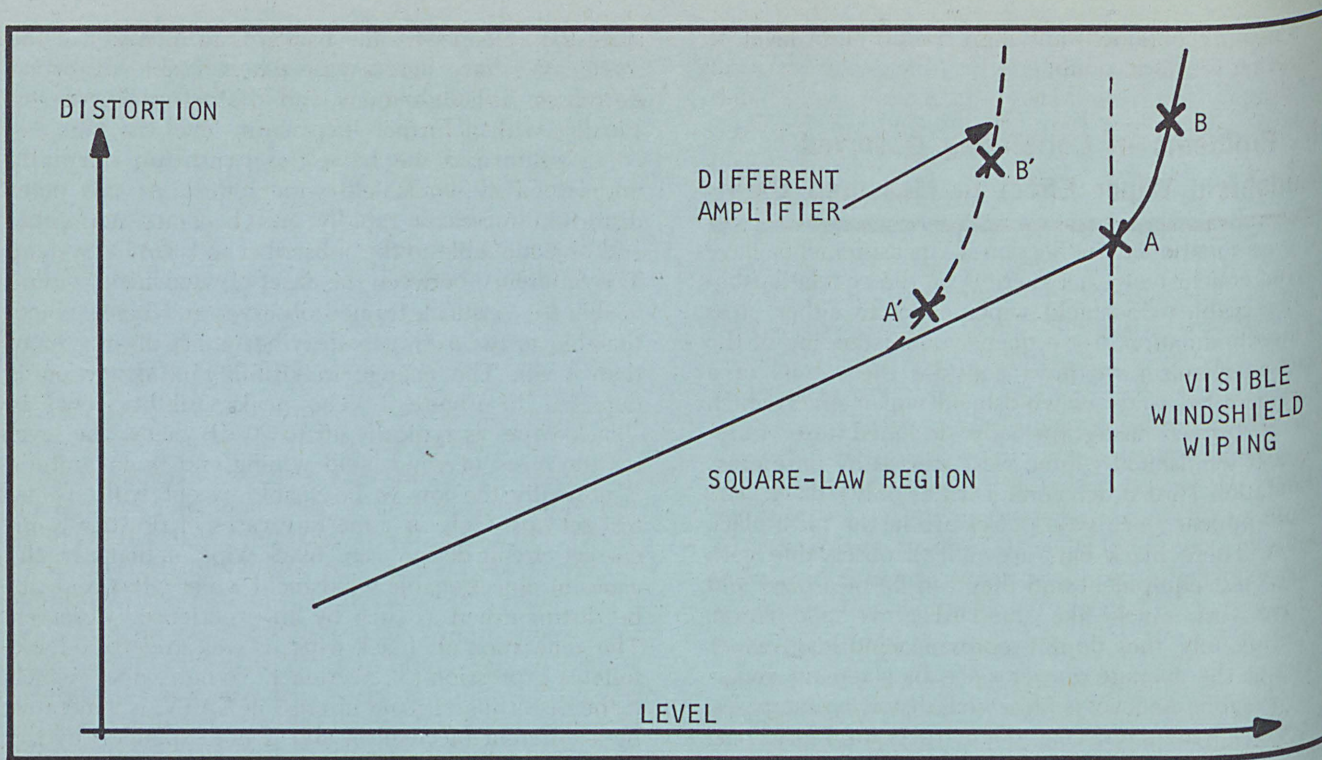

FIGURE 2 TYPICAL DISTORTION VS LEVEL

Distortion as a function of level is shown in Figure 2. At low levels cross modulation follows the square law characteristics of expression (3) and appears as a straight line when plotted directly in dB. Windshield wiping generally coincides with the point of increased curvature of the distortion curve. Therefore, it is often possible to use square law derating below the onset of windshield wiping as a first approximation. In drastically wrong amplifier design a deviation from the square law characteristics may be found, but more commonly such a measured deviation is caused by instrumentation errors due to phase reversals at low levels in combination with direct pickup. Also shown dashed in Figure 2, is the curve of an amplifier with reduced output capability, but with the same characteristics in the square law region. It is clear that a measurement in the square law region is insufficient as a measurement of windshield wiper effect, or to determine output capability.

Another factor which makes correlation of measurements to actually observed distortion difficult, has to do with the timing of sync pulses. If multiple interfering signals exist, the synchronization of sync pulses can lead to peculiar effects. First it should be clear that if all signals, including the desired ones, have common sync pulses, no windshield wiping is possible. The overload level would then be determined by cross modulation of the video signal which occurs at an approximately 8 dB higher level. Although no windshield wiping is possible with synchronized signals, a measurement would indicate a higher distortion level. Next assume two interfering signals which are in sync. In actual distortion visibility tests, two superimposed white bars appear in exactly the same way on the screen as a single white bar, while a measurement would indicate direct addition and increased distortion. By comparison, random sync pulses of two interfering signals appear as a 3 dB lower reading* when measured on a meter while a screen test makes the distortion effect twice as objectionable, because twice as much area is affected.

We have here two cases where a simple distortion measurement, however accurate, gives a reading unrelated to observable windshield wiper effect.

*When read on an oscilloscope the reading is 6 dB lower.

IV Considerations in the Design of Test Signal Generators for Overload Testing

In the course of developing specialized test equipment for windshield wiper testing, research was carried out to obtain correlation to the observable effect on a TV screen. Standard cross or intermodulation test procedures showed no correlation. Only in the normally invisible "black wipe" region does a correlation to third order measured distortion exist.

Since standard test methods failed to show correlation, it was thought that the waveform effect was of significance. Square wave modulated signals were tried and some form of correlation to the visually observed effect was obtained. This correlation was good for some circuits under test and not for others. The problem was traced to the use of square waves for the modulated signal.

Next, pulse modulation was used with pulses 10 μsec wide, spaced at 63.5 μsec. With these signals good visual correlation was obtained regardless of the circuit under test. A test performed with sync pulses having standard "front porch" and "back porch" showed identical results, probably because of the relatively minor waveform change and the inaccuracy of transmitted TV signals which were used for comparison by the direct method.

As a further method of improving correlation, modulation of the desired signal was kept on at all times with the sync pulses of the interfering signal detuned to 10 kHz. The cross modulation components were then separated in a wave analyzer. The test showed no change in readings as long as the peak level of the desired signal was kept constant. This test result greatly simplifies the design and accuracy of a test signal generator since modulation of the desired signal is then not required during the read-out of the distortion products. This would eliminate the need for active filter circuits which introduce another source of inaccuracy.

It appears, therefore, that the simplest test signal, which allows a direct correlation to observable windshield wiper effect, uses pulse modulation similar to standard TV signals without "front" or "back porch." A square wave or sine wave is unsuitable and makes correlation impossible due to time constant effects of different circuits. Standard TV sync pulses may be used but do not seem to offer any correlation advantages while they introduce an accuracy degradation due to higher complexity of generating circuits.

All TV generators should be switchable from CW to modulation without any change in the peak level. Sync pulses should be available both in random and synchronized mode. Modulation depths must be fully adjustable and switchable. All levels must be fully stabilized with respect to temperature and voltage, and frequency should be crystal controlled.*

It is now necessary to discuss the choice of background level used for testing and measurement. Originally, it was thought that 100% modulation would be best (infra-white level) because it might exaggerate the effect, thereby leading to easier measurement. However, it was found, on the contrary, that distortion was less. This is easy to see when we consider that both the desired and the undesired carrier are needed to create this type of distortion. With 100% modulation no carrier exists during the off-periods. The other problem is that since windshield wiper effect is produced by white bars, these become invisible with a white background. With a black background (25% down modulation) the magnitude of the distortion is at the highest possible level both as far as measurement and observation on the screen is concerned, because the desired signal level is maximum in the period between sync pulses and because white bars are most visible against a black background. The desired carrier should therefore be modulated with a black background (25% down) for a worst case effect.

The only difficulty with this level is as a research tool when phenomena such as "black wipe" are to be investigated which become invisible on a black background. There would also be merit in using an average background level (gray at 56.25% down modulation**) because it resembles more closely the actual field condition.

The discussion on background level above relates to the desired carrier, which is the signal under observation or measurement. What about the background level of the undesired or interfering signals? Clearly, distortion is increased as modulation depth is increased. For a worst case condition, the undesired channels should therefore be modulated with a white background level (87.5% down). The determination of the background level to be used as a standard also ties in with considerations in establishing a precise absolute distortion reading rather than some relative figure of merit. For a worst case visual test the undesired signals should be modulated without common sync in random fashion. Common sync is valuable as a research tool and for special applications.

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*Test signals meeting the requirements set forth above have become available recently by using equipment such as TV Carrier Generator, Model 916, by Anaconda Astrodata Co.

**For standardization purposes a gray background level at 50% of sync amplitude might be preferable. This will slightly emphasize the more serious white wipe and de-emphasize the less important black wipe in a visual test.

V The Determination of Absolute Distortion Levels

Many of the foregoing discussions relate to visual observation and an improvement in repeatability and accuracy by the substitution of precise test signals. It is now necessary to examine methods of analyzing and measuring the distortion products so generated in order to arrive at consistent readings.

As was already mentioned, no change in reading was observed with or without modulation of the desired carrier. This test was performed in a rather sophisticated setup with frequency separation of the distortion products from the desired modulation by means of a wave analyzer. For measurement purposes it appears therefore possible to use a CW signal for the desired signal. It is, however, necessary to establish a reference level to which the distortion products are related to, or in other words the 100% or 0 dB reference must be established first. When we read numbers such as distortion is 50 dB down, the question must be immediately asked, "down from what"? As a matter of fact, a good deal of the confusion in windshield wiper distortion measurements is related to the lack of a well defined reference. The following have been used as a reference in the past:

a) The dc-voltage out of the video detector of a field strength meter with and without CW signal applied

b) The dc and ac-voltage of the video detector of a field strength meter with signal applied

c) The peak level of the sync pulses of a modulated signal and the peak level of the modulation of the desired signal

d) The peak level of the modulation signal of the desired signal to the peak level of the undesired modulation with the desired signal unmodulated

Before we examine the various calibration references we should first consider a related number which has been reasonably well accepted. It is generally agreed that 40 dB signal to noise or distortion ratio represents a flawless, studio type picture. This number can be corroborated by considerable published material[4] from different observers under varied conditions. When all the material is sifted and brought upon a common denominator because of different references used, this number is commonly found and it refers to video signal to noise or distortion ratio. Since any disturbance 40 dB down is invisible on the screen, the question must be asked why distortion readings of 55 dB or more down should result at the onset of visible windshield wiper effect. On tracing this behavior further, it is found that unusually low distortion readings are obtained by choice of an incorrect or undefined reference level and incorrect test methods. Actual distortion readings, as we shall see, are much worse than some of the commonly used test methods make us believe.

Going back to the display on the TV screen, full modulation is determined by black and white levels. This might be considered the ultimate reference to which everything must be related.

In terms of level, white and black are standardized at 12.5 and 75% respective amplitude of the sync level. If the top of the sync pulse were used as a reference, which might be convenient for measurement purposes, distortion readings obtained will be lower by a constant factor. Simple calculation shows this constant to be 4.1 dB, thus an "actual" reading of 40 dB will appear to be 44.1 dB down when referred to the top of the sync pulse. The difference of average picture level to top of sync pulse is found as 7.2 dB, hence a reading of 47.2 dB down from the sync pulse level is obtained when the primary reference is average picture modulation.

In any type of modulation distortion testing, it is essential to calibrate not only the rf-carrier, but also its modulation level (see expression (3), Section I). This is common engineering practice and is for example, called out in the IEEE standards on distortion testing[5]. By modulating the desired carrier first, a precise 100% reference is established. If the waveform used for calibration is identical to that used for modulation of the undesired carriers, waveform errors drop out regardless of the meter used in the final readout. By this method, errors due to detector nonlinearities and rectification efficiency changes with level are greatly reduced.

Considering the references given above, we find that in a) the references are unrelated to the signal, but rather to the detector dc-efficiency at high level to the residual dc voltage; for example, the static charge of a vacuum tube diode varies with tube life and circuit from 0 to about −2 volts. In b) we are comparing a dc voltage determined by diode linearity to the rectified audio signal which includes diode efficiency and waveform distortion. Method c) uses sync pulse tips as reference when the undesired modulation has a different waveform. Detector nonlinearity directly affects the reading. Method d) is the accepted engineering method which avoids nonlinearity and waveform errors. It is used for all types of communications equipment in tests for cross and intermodulation and applies as well to CATV equipment where high accuracy is required.

A comparison test of method a), using a popular field strength meter, with method d) showed that method a) produced an incorrect, 6 dB lower distortion reading for a given amplifier. The more correct method b) was off 4 dB for this particular case.

It is clear from this discussion that for calibration the desired signal will have to be modulated first with the waveform and background level as discussed above. Calibration voltage is the detected peak to peak voltage. The undesired signals are then modulated with the same waveform and distortion may be read. Even with this basically correct method several possibilities must be distinguished:

1) If the desired signal is kept modulated at all times during the test, detector nonlinearities and changes of detection efficiency drop out. However, it will be necessary to modulate the desired and undesired signals at a slightly different frequency to be able to separate the distortion products from the desired signal. This can lead to waveform errors plus time constant errors of the circuit under test. Also, the added complexity of equipment adds a greater uncertainty factor; however, this method allows probably the most accurate absolute distortion measurement. Also, visual observation and correlation is readily possible.

2) With the desired carrier modulated on calibration only, no waveform error is introduced if the same waveform is used to modulate the undesired carriers. The change in waveform of the desired carrier may result in a different dc-level of the demodulator which in turn can affect detection efficiency and produce a certain error in absolute reading. This error may be made small by careful detector design and choice of signal levels. The great advantage of this approach is relatively simple test equipment and repeatable, precise relative readings.

3) There are a number of ways of obtaining meaningful distortion readings which, however, are only relative. It is possible to increase the reading by simulating a worst case condition. Such methods may lead to increased relative accuracy by avoiding problems with noise, hum, etc. Typically, CW or black background is used for the desired carrier and 100% or white modulation for the undesired signals. This approach combines advantages of method 1) with 2). There is a possibility of waveform error which is avoided by an oscilloscope (peak to peak) readout. However, in a metered reading a correction must be made.

It is immaterial in all these cases if the reference used is the black to white level, the black to zero level, or the sync to zero level since all are related by a constant and a reading is readily converted to a different reference, such as the absolute reference of black to white level, which is the basic video reference.

VI Practical Considerations in Testing CATV Amplifiers

Even with well founded test procedures and accurate instrumentation, there are additional precautions which must be taken with CATV amplifiers due to their particular characteristics. Generally, a CATV amplifier must be operated near its optimum gain setting in a CATV system in order to achieve highest system dynamic range[6]. This optimum gain setting, or spacing ranges between 18 and 28 dB for well designed transistorized amplifiers. Optimum spacing can be directly measured on an individual amplifier and exact values are available from manufacturers. It is clear that all measurements to be meaningful should be taken under the identical amplifier settings as used in the system; this includes in particular:

a) Gain and equalization; for extra accuracy, verify frequency and cable temperature of specifications. Frequencies range from 211.25, 213, 216 to 220 MHz. Temperatures may be system median, room temperature at 68, 75°F or others. Amplifiers are designed to equalize cable of a length determined by the gain. All-band amplifiers will provide correction from 50 to 220 MHz. The flatness of equalization is important and its accuracy enters into the distortion reading. Before any testing, the amplifier should therefore be precision-aligned with the correct length of cable. Equalizers and other switches and controls should be set as they would be in system usage.

NOTE: For comparative tests of amplifiers of different types and makes, it is necessary to test all amplifiers under identical conditions, that is aligned for the same length of cable (gain and equalization). It will not do to compare one amplifier at a high gain setting and another at a low gain setting since then dynamic range and system derating vary, thereby leading to fallacious interpretations. Alternately, the proper mathematical correction may be applied to readings taken of different amplifiers at different gain settings.

b) System tilt. This is not an amplifier adjustment — they were already completed under a) above — but rather refers to the proper levels of the test signals. If an amplifier is operated in a system under Half-Tilt, measurements should be also performed under Half-Tilt. A test with flat input signals (test signals of equal amplitude), results in Full-Tilt operation and a meaningful number is obtained only if this amplifier is also used in this tilt mode in the system. For Half-Tilt operation, it will be necessary to connect cable of one half the normal spacing between the flat test signals and the amplifier under test. Alternately, the test signals may be preset, but this method is less accurate.

c) Broadband effects. Modern CATV amplifiers are designed to operate without jumpers in the CATV system. Unavoidable mismatches cause flatness errors with jumper cables. To avoid these in overload testing, coaxial attenuators without jumpers should be connected directly to the amplifier where a problem might exist. Lead lengths in excess of 1 inch are to be avoided. An alternate is to use the correct length of system cable directly. A typical error of 3 dB has been demonstrated when a jumper cable was used in overload testing even with precision test equipment.

d) Powering. Ideally all equipment should be powered for testing in the same way as in the system, that is, via AC cable powering. For convenience purposes, direct DC powering is often used; however, this technique must be verified for each type of amplifier for accuracy in order to avoid misleading readings.

e) AGC-amplifiers. Various AGC principles are used in CATV AGC-amplifiers. Those using open-loop thermal circuits normally do not require special precautions. In closed-loop systems overload of the output stage is not directly measurable due to AGC action which limits overload to the early stages. A more meaningful test results by opening the AGC loop of such an amplifier. Measurements are then taken with a fixed dc-bias applied to the AGC circuit. The correct bias for the spacing under test must be determined on the alignment bench. Logically, tests should be extended to cover the whole specified gain range of the AGC amplifier by varying the applied dc-voltage. In closed-loop testing of AGC-amplifiers it is important to apply the correct input signal levels with the proportionate change at all channels as in the system. This is also true for pilot carriers if used. Overload readings are then expressed in terms of input overload level at Channel 13 rather than the usual output overload reading.

f) Multichannel operation. Amplifiers designed for all band operation must be tested with 12 test signals. Extrapolation from fewer signals has proven unsatisfactory because the relationship varies with type of amplifier and system mode.

In addition to the rules given above, when a metered reading is used it should be checked for hum and noise. With an oscilloscope a reasonable accuracy is still possible even when hum or noise are present. However, a meter in conjunction with a wave analyzer or active audio filter leads to a more accurate and direct reading than an oscilloscope.

Testing may be performed at levels below overload, but readings so obtained are generally not related to windshield wiping, because they are caused by a totally different mechanism. Hence, measurements taken at the normal derated system level have meaning only when performed for the total maximum cascade[7] of amplifiers. Such a test is practical only in a working system and is normally done routinely to establish system safety margins. For individual amplifiers, overload level is synonymous with the onset of windshield wiper distortion, while testing at lower levels may be useful to investigate other types of distortion. For the same reason, does a low level measurement in no way give an indication of the actual output capability of an amplifier.

APPENDIX I

MATHEMATICAL ANALYSIS OF WINDSHIELD WIPER EFFECT

We express amplifier nonlinearities by the power series.

$$e_o = a_o + a_1 e_i + a_2 e_i^2 + a_3 e_i^3 + \dots \quad (1a)$$

and apply as input signal the sum of two modulated rf-signals

$$e_i = E_d \cos \omega_d t + E_u \cos \omega_u t \quad (2a)$$

where $E_d = e_d (1 + m_d \cos p_d t)$
and $E_u = e_u (1 + m_u \cos p_u t)$
with e = peak voltage
m = modulation index
ω = rf-frequency in radians
p = modulation frequency in radians
subscript d = desired signal
subscript u = undesired signal

Expansion of (1a) and separation of the distortion products leads to the following terms:

a) a low frequency and dc-component:

$$a_o + a_2 (E_d^2 + E_u^2)/2 + \text{term with } a_4 + \dots \quad (3a)$$

b) a modulation term of the desired carrier:

$$a_1 E_d \cos \omega_d t \; [1 + 3 a_3 E_d^2 / 4 a_1 + 3 a_3 E_u^2 / 2 a_1 + \dots] \quad (4a)$$

c) a modulation term of the undesired carrier

d) second and higher order harmonics of the desired and undesired carriers

e) intermodulation products of desired and undesired carriers

By substitution of the expressions for E_d and E_u in (2a), we see that cross modulation is caused only by the last term in (4a). None of the other terms can produce modulation distortion of the desired carrier. Expansion to higher orders of (1a), leads to additional terms in (4a); however, it is easy to show that no higher order products nor any combination thereof can lead to a distortion product of the form $a_1 E_d \cos \omega_d t \, (1 - k \, m_u \cos p_u t)$ where k is a constant, which is required to explain observable windshield wiper effect. It is clear now, that the generation of distortion based on any single nonlinear effect of any order does not produce windshield wiper effect although it explains all other types of rf-distortion such as intermodulation products of all orders, as well as all types of cross modulation, mixing, frequency conversion, multiplication and the generation of harmonics. Since even higher order nonlinearities cannot explain windshield wiper effect, we must now look for a different mechanism and it will be sufficient to limit our investigation to the terms up to the third order of the power series as given in expression (1a). We must include the third order term because it is required to produce observed black wipe (simple first order cross modulation).

We consider now a two-stage process and examine in particular the base band products. Let us assume that at some high level point additional distortion is generated by a different high level nonlinearity expressed by

$$e_o = b_o + b_1 e_i + b_2 e_i^2 + b_3 e_i^3 + \ldots \qquad (5a)$$

Substituting terms (2a), we obtain base band frequencies as in (3a) above, which contain a term $b_2 E_u^2 /2$ and this in turn can be expanded into a dc-component and a term $b_2 e_u^2 m_u \cos p_u t$ (and a second harmonic term), that is demodulation or rectification has taken place. The term b_3 does not contribute to the demodulated signal. Alternately, we can assume detection in the input circuit of the amplifier at high signal levels. This will also lead to a dc-term and the demodulated signal $\eta\, e_u m_u \cos p_u t$, where η is the detection efficiency. This demodulated signal together with the signals of expression (2a) are now applied together to a new* power series of nonlinear amplification (6a).

$$e_o = c_o + c_1 e_i + c_2 e_i^2 + c_3 e_i^3 + \ldots \qquad (6a)$$

where c = coefficients of high level nonlinearities

The modulation polarity of the added demodulated signal is negative with respect to the phase of the modulation envelope of the carrier of (2a). This is so because an increased signal level into any active element (tube or transistor) produces a base band output upon rectification which is in the direction to turn the device off.

The new input signals are now

$$e_i = E_d \cos \omega_d t + E_u \cos \omega_u t - E_b \qquad (7a)$$

where $E_b = b_o + b_2 (E_d^2 + E_u^2)/2$ based on (5a)

Quite generally E_b contains a dc component which is of no interest, and the demodulated undesired signal which we may write as $E_b = E_o + k m_u \cos p_u t$

Substitution into (6a) and expansion leads now to the following modulation product of the desired carrier:

$$c_1 E_d \cos \omega_d t\, (1 - 2c_2 E_b/c_1 + \ldots) \qquad (8a)$$

The second term in brackets is the countermodulation term. Other, higher order terms are unrelated to windshield wiper effect. Expanding (8a) and adding the original cross modulation term of (4a) we find for the desired carrier, modulated by the undesired modulation

*because of the changed dc-component

$$\text{DC-COMPONENT} \quad - 2 c_2 b_2 e_u^2 m_u \cos p_u t + 3 a_3 e_u^2 m_u \cos p_u t =$$
$$= \text{DC-COMPONENT} \quad + e_u^2 m_u \cos p_u t\, (-2 c_2 b_2 + 3 a_3) \qquad (9a)$$

For term $b_2 = 0$ (no demodulation), modulation of the desired carrier by the undesired signal is possible only through term a_3 which produces in phase cross modulation (black wipe). At some, much higher signal level rectification begins, expressed by term b_2. The demodulated signal is in turn modulated on the desired carrier by a following second order nonlinearity, expressed by c_2, and produces a countermodulated signal which gradually cancels the cross modulated signal and eventually with increased level leads to visible windshield wiper effect.

The sum total of windshield wiper effect is therefore explained by three uncorrelated distortion producing mechanisms, which are functions of the applied signal level as follows:

1) At low levels certain nonlinearities (coefficients a) produce standard cross modulation. For this distortion to occur third order distortion is necessary (terms with a_3).
2) As signal level increases, a new independent mechanism (expressed by coefficient b) produces rectification (demodulation) ahead of the actual amplification. This process produces also an input dc current and results in new nonlinearities of the amplifier (coefficients c).
3) Baseband frequencies together with second order distortion c_2 of the amplifier result in countermodulation which cancels the original cross modulation and produces what is known as windshield wiper effect (white wipe).

In summary, we can say that windshield wiper effect is produced by countermodulation, which can only be produced by demodulation and subsequent modulation. Demodulation can be produced by normal rectification (diode action of grid-cathode or base-emitter) or any second order nonlinearity (square law detection). Modulation is then produced by following second order nonlinearities. The process of countermodulation is a high level effect, not present at lower levels.

Normal cross modulation tends to decrease windshield wiper effect because it is out of phase. Cross modulation is caused by third order nonlinearities.

The mechanism of the generation of windshield wiper distortion might then be represented by an active nonlinear amplifier having a linear input impedance, where this linear input impedance becomes nonlinear at some high signal level (overdriven input).

The mathematical analysis shows that windshield wiper effect is not related to cross or intermodulation. However, there exists a loose indirect relationship to high-level intermodulation because both it and countermodulation contain a common second order term (c_2).

APPENDIX II

TEST DATA FOR WINDSHIELD WIPER DISTORTION

Amplifier Type:__________ Model:__________ Manufacturer:__________ Serial:__________

Amplifier equalized for__________dB of cable at__________ MHz and__________°F

Flatness ± __________ dB from__________ MHz to__________MHz

Number of test signals__________ Frequencies __________

Modulation of undesired signal: TV Signals: __________ Random Sync:__________ Common Sync:__________

Modulation depth of
undesired signal: TV Signal:__________ White:__________ Gray:__________ Black:__________

Modulation of
desired signal: TV Signal:__________ Blank Carrier__________ Sync Modulated:__________

Modulation depth of
desired signal: TV Signal:__________ Black:__________ Gray:__________ White:__________

Width of sync pulses:__________μsec Repetition Rate:__________μsec

Modulation of desired
signal for measurement: CW Signal:__________ Changed Reptition Rate:__________μsec

Overload level determined as: __________ dB below onset of visible windshield wiping

__________ dB below modulation of desired carrier

Channel of Observation or Measurement	Overload Level Read on Channel	Output Overload Level in dBmV	Input Overload Level in dBmV
13			
12			
11			
10			
9			
8			
7			
6			
5			
4			
3			
2			

Tilt of output signals: Half-Tilt:__________ Full Tilt:__________ Other:__________

Tilt of input signals: Half-Tilt:__________ Flat Inputs:__________ Other:__________

Powering Direct dc:__________ Direct ac:__________ Cable Powered ac:__________

AGC-Test: Open Loop:__________ Closed Loop:__________

Residual Reading: Hum:__________ Noise:__________ Other:__________

APPENDIX III

REFERENCES

1) "Design of Low-Noise Transistors Input Circuits" (book), Hayden 1964, pg. 43 ff.

2) "Test Simulates TV Windshield-Wiper Effect," *Electrical Design News*, Sept. 1963

3) CATV System Engineering, Tab Books, 2nd edition 1967

4) See Reference 3, Literature 1-6 and 9-17.

5) IEEE Standard, 48 IRE 17 SI

6) See Reference 3, Chapters 4 and 7.

7) "Calculating Overload Threshold for Cascade Amplifiers," *Electronic Equipment Engineering*, July 1964

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CHAIRMAN TAYLOR: Thank you very much. (Applause) Do we have questions?

Can we make amplifier tests without knowing the exact distortion producing mechanism?

MR. RHEINFELDER: Yes. The important point is, however, that all tests should in some way relate to performance in the CATV system in order to be meaningful. As has been explained in my paper, there are three types of distortion which, singly or in conjunction, may produce overload distortion in CATV systems. These types of distortion, all familiar from communications theory, are cross modulation, intermodulation and countermodulation. Since windshield wiper effect is caused by countermodulation, tests for cross or intermodulation are of minor importance for CATV. Even if you test two amplifiers under the same conditions, if the test does not relate to observed performance in the field, such a test would be meaningless. Instead, a test for countermodulation should be performed.

If you were trying to correlate a measured distortion number to a visual field test, what would be the accuracy of measurement?

MR. RHEINFELDER: The accuracy of the visual test by itself is not very high. This is in more detail discussed in the printed copy of my paper which is available at the booth. As discussed in this paper, one way to increase the accuracy of the live signal test is to use a reference amplifier which is then kept as a standard, and everything is referred to it. If you use this method and make the necessary corrections, you eliminate the subjective effects and eliminate errors in the TV set adjustments, and then you achieve an accuracy of about plus minus one db. From an evaluation standpoint you can live with it, but as a research tool you cannot.

Can windshield wiper effect be caused by cross modulation?

MR. RHEINFELDER: In my own experience and that of all my associates in CATV, overload in CATV systems is evidenced by the onset of white bars. These cannot be caused by cross or intermodulation; that is, simple second or higher order effects, but are caused by countermodulation which is a two-stage second order effect.

Can third order distortion produce white windshield wiping?

MR. RHEINFELDER: The answer is no. Third order distortion does not produce a phase reversal which is the prerequisite for the appearance of white bars.

CHAIRMAN TAYLOR: Are there any other questions? If not, I want to thank the members of the panel for their participation this afternoon, and thank you all for your attention.

(The session adjourned at five-fifty o'clock p.m.)