FEEDFORWARD APPLIED TO CATV AMPLIFIERS

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ABSTRACT

The small size, stability, and efficient use of power of hybrid integrated circuits makes feedforward an attractive design technique for CATV amplifiers. This paper discusses the general design technique of feedforward and the resultant advantages and disadvantages. The most significant advantage is the reduction of all distortion products appearing at the output of an amplifier.

Introduction

In the late 1920's H. S. Black rigorously characterized and patented the technique he described as feedback. In the succeeding years feedback has been used in virtually every area of active circuit design. A few years prior to his work on feedback, Black invented and patented the technique of feedforward. By comparison with feedback, feedforward has found very limited usage. In recent years it has been shown(1,2) that feedforward, when applied to a wide band amplifier can produce some very attractive properties. The most significant advantage is the reduction of all distortion products at the output of the amplifier. Perhaps the most significant disadvantage of feedforward is the extra circuit complexity involved. However the small, stable and efficient integrated circuit amplifiers currently available tend to offset this disadvantage and make feedforward an attractive design technique for CATV Amplifiers. This paper will discuss the theory of feedforward and its application to CATV amplifiers.

To best understand the principle of feedforward consider the properties of a wide band RF amplifier as used in CATV. Such an RF amplifier performs three operations upon the input signals applied to it: (1) amplifying the signals, (2) delaying the signals, (3) and adding errors in the form of noise and distortion products to the signals. The first operation, amplification, is the reason for the amplifier's existence and nothing more need be said about it. The second operation, delay, is an unavoidable consequence of the first operation. The delay is generally uniform across the bandpass of the amplifier and small, perhaps no more than the delay provided by two feet of coaxial cable. The delay is insignificant when added to the delay of a cable system made up of many thousand feet of cable. The last operation, the added error signals, is another unavoidable consequence of amplification and, since these errors ultimately limit the performance of the system, it is desired to minimize them. If the error signals could be isolated from the fundamental signals then one could reinsert the errors back into the main signal path in such a way as to eliminate them. In order to isolate the errors, the output can be smapled and subtracted from a sampled portion of the input. However the output is no longer synchronous with the input, having been delayed by the amplifier. We cannot undelay the output, but we can delay the sampled input by an amount equal to the amplifier delay. Having thus synchronized the sampled input and output, the two can be subtracted leaving only the errors. Thenisolated error signals, having been scaled down by the sampling networks, must be amplified before being reinserted into the main signal path. The delay resulting from this amplification must be offset by an equal delay in the main signal path before complete cancellation can occur. It is important to recognize the significance of the delay caused by the amplifiers. Although the delay is small in terms of the system delay, it is large when compared to the period of the signals involved. Thus comparing the output to the input directly and modifying the input (feedback) is not possible. Feedforward recognizes the passage of time and compensates for it always in the forward direction.

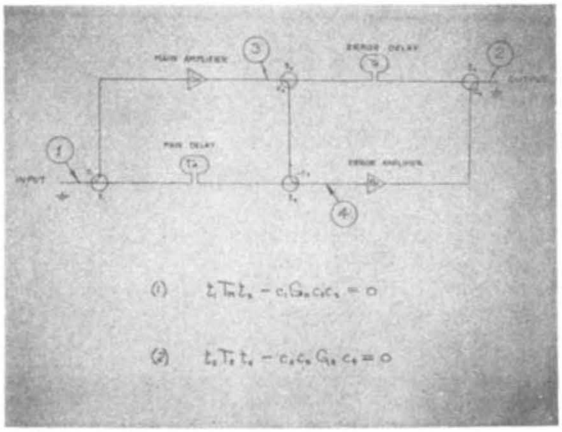

Figure 1

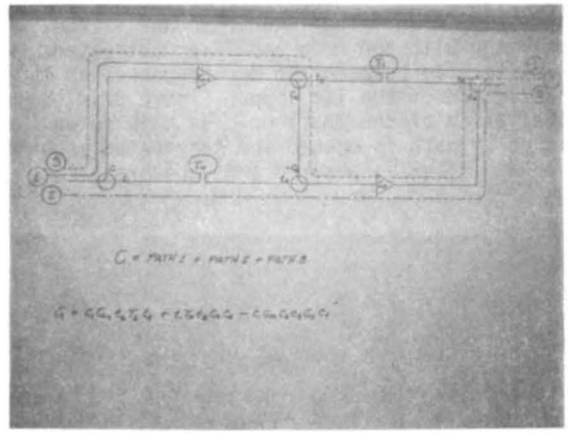

Figure 2

Fig. 1 is a block diagram of a typical feedforward amplifier. The points in the diagram indicated by 1 and 2 represent the input and output of the amplifier respectively while points 3 and 4 are internal to the network. Between points 1 and 4 there are two possible paths for the input signal to take. The following constraint is placed upon these two paths.

$$-C_1C_2C_3G_M + t_1T_M t_3 = 0 \qquad (1)$$

And similarly between points 3 and 4

$$t_2T_E t_4 - C_2C_3G_E C_4 = 0 \qquad (2)$$

Equation 1 is said to describe the 1st or main loop while equation 2 describes the 2nd or error loop. The 1st loop cancellation (equation 1) means that any signal applied to port 1 does not appear at port 4. Hence any input signal is not influenced by the cancellation of the 2nd loop by virtue of the 1st loop cancellation and is coupled directly to the output through the error delay path. However at the output of the main amplifier there are "error" signals as well as amplified input signals. The error signals are the noise and distortion products generated by the main amplifier. They are, by definition, not present at the input and hence are not cancelled at point 4. Hence equation 2 applies to these error signals and they appear at the output reduced by the cancellation of the 2nd loop. These two amplifiers then, connected as indicated in figure 1, cancel all the noise and distortion generated by the main amplifier. The noise and distortion generated by the error amplifier of course appear at the output uncancelled. However, since the error amplifier nominally carries only error signals, which hopefully are several orders of magnitude below the fundamentals, it can have a low power front end to optimize its noise figure, and a medium power output to keep the distortion down.

Of course the success of such a feedforward amplifier depends on the degree of cancellation that can be reliably accomplished. Fig. 2 is a photograph of the cancellation of the 1st loop. In order to measure this cancellation the error delay path was opened and terminated thereby disabling the 2nd loop. The upper response represents the setup with the main amplifier unpowered--namely the transmission through the main delay with the error amplifier acting as simply a post amplifier. The lower response is the same setup with the main amplifier activated. The difference between the two responses is the cancellation of the 1st loop. Figure 3 is the cancellation of the 2nd loop. In this setup the main delay path is opened and terminated and the error amplifier is powered and unpowered.

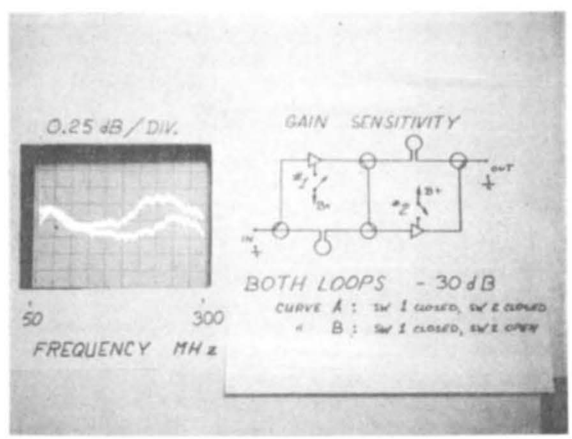

Figure 3

Both loops were aligned for the best possible cancellation, approximately 30 dB worst case. To produce 30 dB cancellation across the band the two paths involved must match to within 0.27 dB in amplitude or 1.82 degrees in phase. Such a matching of the paths appears to be as good as one can do using the integrated circuit amplifiers currently available. The phase matching of about 2 degrees out of a total path length of some 500 degrees is perhaps a more severe requirement than the amplitude match of .27 dB when compared to the amplifier gain of about 30 dB. Moreover to maintain these kinds of tolerances over the temperature variations encountered in CATV systems would be at the least very difficult and perhaps impossible. Our measurements indicate that, given a 30 dB cancellation at room temperature, the cancellation degrades to some 24-20 dB at the extremes of temperature. This change does not represent much drift between the two paths involved and is very encouraging. However rather than either accepting this performance or attempting thermal compensation to improve this performance, a different alignment strategy was sought. Before describing this alternate alignment strategy, some of the unusual properties of a feedforward amplifier will be discussed.

One of the properties of feedforward is parameter desensitization. Specifically the overall gain of a feedforward amplifier is remarkably independent of the gain of either of the internal amplifiers. Figure 4 demonstrates this behavior.

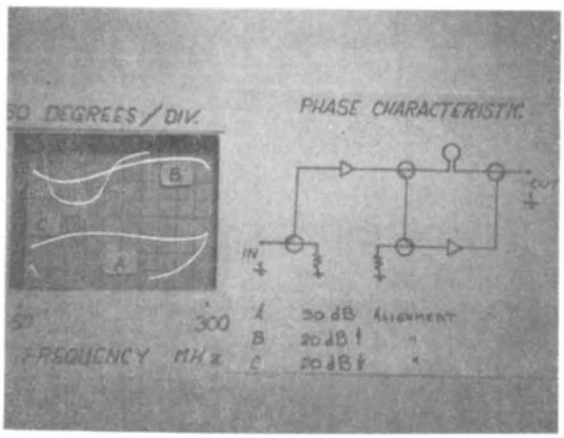

Figure 4

From figure 4 it can be seen that the overall gain expression is equal to the sum of three expressions. Because of the constraints placed upon the two loops, each of these three expressions can be shown to be equal to one another except that path 3 has a negative sign associated with it. Depending on how the substraction is carried out, the gain can be represented by either the expression for path 1 or path 2. It is easy to see intuitively and arithmetically that when either amplifier gain is made to go to zero the overall gain is unchanged. Figure 5 is a double exposure photograph of the frequency response of a feedforward amplifier. One exposure is with both loops operating normally. The 2nd exposure is with the error amplifier unpowered. The total change worst case is approximately .3 dB. Since both loops are not aligned perfectly--approximately 30 dB cancellation worst case--some gain change is to be expected, in this instance about .3 dB. The expressions predicting this behavior are derived in Appendix A.

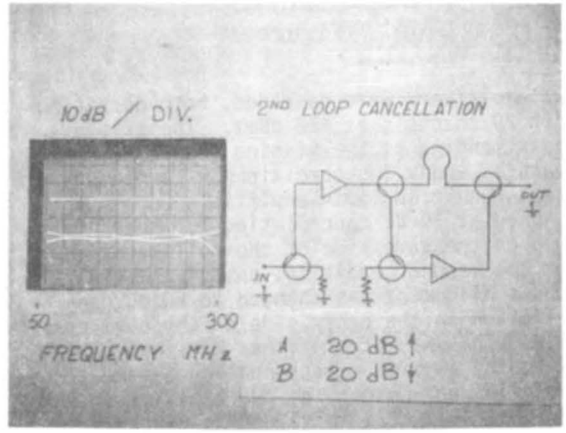

Figure 5

Another parameter that is desensitized upon the application of feedforward are input and output impedances. Specifically the output impedance of the main amplifier can be completely mismatched to optimize its output capability and the input impedance of the error amplifier can be completely mismatched to optimize its noise figure. Neither mismatching has a significant effect on the input or output match of the overall amplifier. With the first loop cancelling, virtually zero input signal arrives at the input of the error amplifier. Hence the input impedance of the error amplifier is "improved" by the cancellation of the first loop. On the output side the situation is slightly different. Any signal impressed upon the output does arrive at the output of the main amplifier via the error delay path. However, any reflected component of this signal is regarded as an "error" signal by the 2nd loop and is subject to the cancellation of the 2nd loop before reappearing at the output. The 2nd loop "improves" the output match of the main amplifier.

Another very interesting property of feedforward is the resultant phase of the distortion products after cancellation by the second loop. As we have seen earlier changing the gain of the error amplifier has a minimal effect of the overall gain. It can be easily shown that the phase characteristic is also unaffected. Hence small gain changes in the error amplifier produce nominally zero changes in the amplitude and the phase of the fundamental signals appearing at the output. However error amplifier gain changes do have a direct bearing on the resultant distortion products appearing at the output. Assume that the error amplifier gain is adjusted for the best possible cancellation of the error loop--say 30 dB cancellation. If the error amplifier gain is increased 1 dB, the cancellation goes to approximately 20 dB and the phase characteristic of the error loop is dominated by the error amplifier path of the loop. If the gain of the error amplifier is decreased by 1 dB, the cancellation again is 20 dB but the phase is dominated by error delay path of the error loop. The error delay and the error amplifier paths have identical phase characteristic except for a 180 degree offset. On either side of the best null position the phase characteristic of the error loop undergoes a complete inversion.

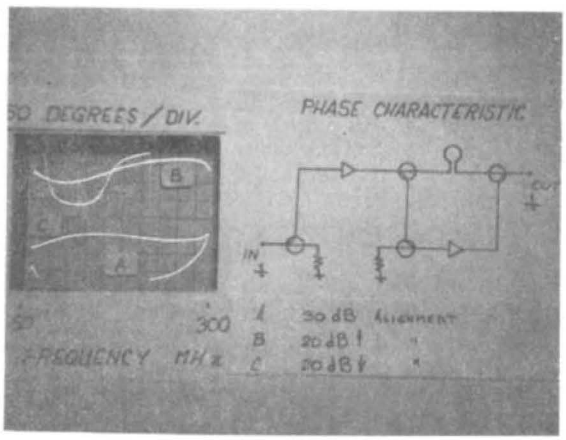

Figure 6

Figure 6 shows the cancellation of the 2nd loop with the error amplifier gain first increased and then decreased 1 dB from the best alignment position. The cancellation in both instances goes to approximately 20 dB. Figure 7 shows the phase characteristic of the error loop for three positions of error amplifier gain--best null, ± 1 dB from best null. A linear phase characteristic is subtracted from the setup so that the curves may be more easily compared. The best null phase curve undergoes a number of transitions where the amplitude characteristic of the two paths involved cross one another. The 1 dB phase curves are about 180 degrees offset from one another. This means that the phase of the distortion products produced by a feedforward amplifier can be made to undergo an inversion without affecting the fundamental signals.

This unusual property of feedforward provides the basis for what was described earlier as an alternate alignemnt strategy. Each amplifier's error loop is slightly misaligned on one side or the other of the best null. Actually each amplifier would be aligned on both sides of the null and provided with a switch to select the desired mode.

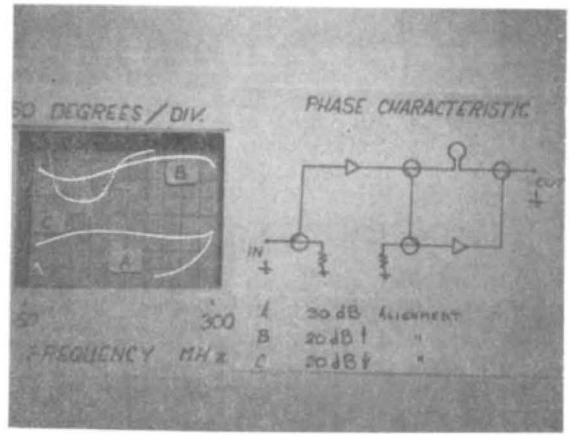

Figure 7

In a cascade of such amplifiers alternate amplifiers would be operated in alternate modes. The distortion generated by the 1st amplifier would tend to be cancelled by the distortion of the 2nd amplifier; the distortion of the 3rd cancelled by the 4th, etc. The penalty paid by individual amplifier misalignment would be offset by cancellation between cascaded amplifiers. Another advantage of this alignment strategy is temperature stabilization. Small changes in the gain of the error amplifier have a large effect on the 2nd loop cancellation at the null position. As the alignment is moved away from the null, small gain changes have a smaller and smaller effect on the 2nd loop cancellation. It seems clear that an "optimum misalignment" must exist to minimize the distortion at the end of a cascade at the worst condition of temperature. At this writing work is proceeding to find this optimum.

A number of measurements were made on a feedforward amplifier with a 30 channel set of CW signals and a spectrum analyzer. Figure 8a is the output of the amplifier with the error amplifier unpowered. The amplifier was operating with 29 channels (2-13, A-F, H-R) at +52 dBmV flat. Figure 8b is the same situation with the error amplifier powered. Since this amplifier is operating with 30 dB cancellation it is not surprising to see all the distortion products go below the noise floor. The remaining spurious signals in figure 8b in the FM band and at channel 7 sound were traced to off air interference and were not generated by the amplifier. Figure 9 is a double exposure under the identical conditions of Figure 8 except that the spectrum analyzer dispersion was reduced to 50 kHz per division centered on the missing channel G. The distortion is the spectrum of the some 200 odd triple beats falling on or around channel G carrier. It is evident that the full benefit of the 30 dB cancellation is achieved. Figure 10 demonstrates the effect of cancellation between cascaded amplifiers.

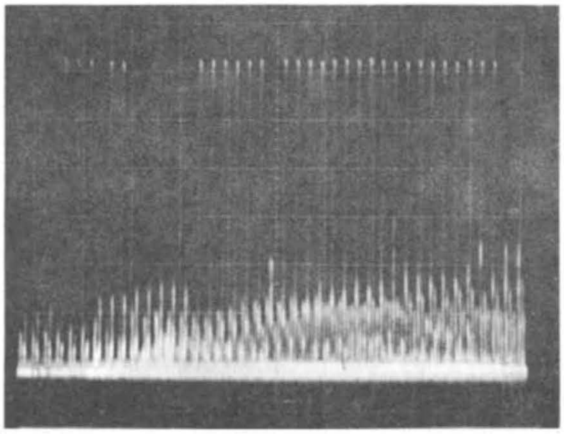

Figure 8a

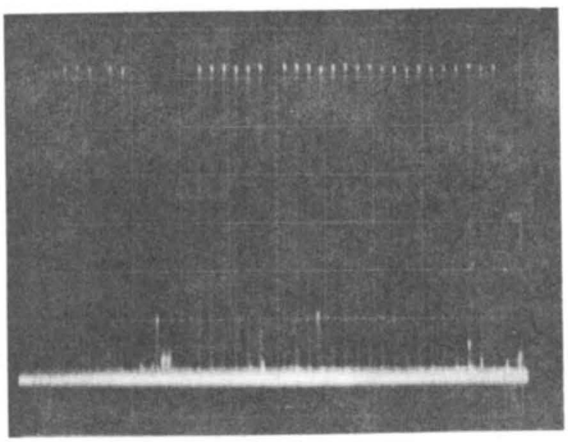

Figure 8b

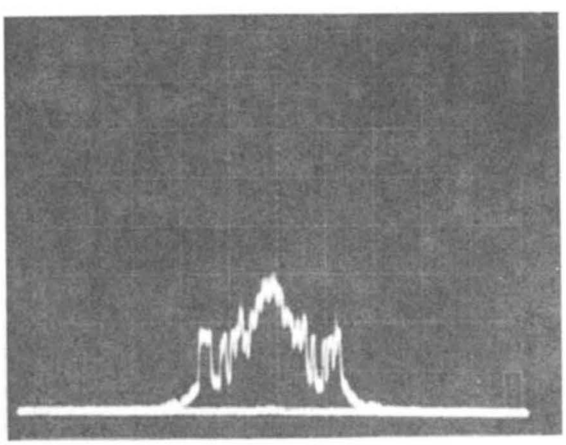

Figure 9

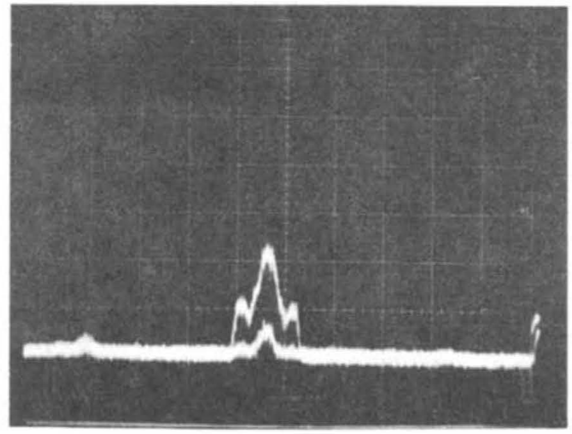

Figure 10

Two amplifiers were cascaded, both operating with 29 channels at +52 dBmV. The triple beats landing at the missing channel G were measured under two conditions. For the first condition, both amplifiers were aligned at 20 dB cancellation for the 2nd loop on the same side of the null position. For the second condition, one of the amplifier's alignment was changed to 20 dB cancellation on the other side of the null position. This was accomplished by simply switching in 2 dB of attenuation in the error amplifier path of one of the amplifiers. The 2 dB pad switch allows a double exposure to conveniently record the difference between the two conditions. Figure 10 shows the distortion falling about 16 dB when the amplifiers are operated in opposite modes.

All the distortion measurements taken are in very nice agreement with the performance predicted by the linear measurements taken on the individual loops. The results of these measurements indicate that feedforward applied to CATV amplifiers can yield a significant reduction in the total distortion generated by a cascade of amplifiers.

Appendix A

From Figure 4,

$$G = C_1 t_2 t_4 T_E G_M + t_1 t_3 C_4 T_M G_E - C_1 C_2 C_3 C_4 G_M G_E. \qquad (3)$$

Differentiating with respect to G_M

$$\frac{\partial G}{\partial G_M} = C_1 t_2 t_4 T_E - C_1 C_2 C_3 C_4 G_E \qquad (4)$$

Multiplying both sides by $\frac{G_M}{G}$

$$\frac{\frac{\partial G}{G}}{\frac{\partial G_M}{G_M}} = \frac{G_M C_1}{G}\left(t_2 t_4 T_E - C_2 C_3 C_4 G_E\right) \qquad (5)$$

Substituting in equations (1) and (2) and rearranging yields

$$\frac{\partial G / G}{\partial G_M / G_M} = \frac{t_2 t_4 T_E - C_2 C_3 C_4 G_E}{t_2 t_4 T_E} \qquad (6)$$

The right hand side of equation (6) is simply the cancellation of the 2nd loop. The equation says that percentage gain change of the feedforward amplifier is equal to the percentage gain change of the main amplifier multiplied by the cancellation of the 2nd loop.

References

(1) H. Seidel, "A Feedforward Experiment Applied to an L4 Carrier System Amplifier," IEEE Trans. Comm. Tech., Vol. Com-19, June 1971, pp.320-325.

(2) R.G.Meyer, R.Eschenbach, and W.N.Edgerly,Jr., "A Wide-Band Feedforward Amplifier," IEEE Solid State Cir., Vol. SC-9, Dec. 1974, pp.422-428.