BODE'S VARIABLE EQUALIZER

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The Bode Equalizer, an adjustable equalizer circuit long used in the telephone industry at voice carrier frequencies, is finding its way into the CATV industry at VHF frequencies. This type of circuit provides superior cable tracking accuracy and ease of adjustment, compared to circuits used in the past. The design of these equalizers can be accomplished by a straightforward bench procedure, or by computer aided design techniques. The theory, design, and application of the Bode Equalizer are discussed in this paper, and a sample CAD program used in its design is presented.

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Introduction

The CATV industry has borrowed terminology as well as technology from a number of other fields. One obvious source is the telephone industry, especially carrier telephony. This paper discusses one recent acquisition.

In the April, 1938, Bell System Technical Journal, H. W. Bode described a type of variable equalizer circuit, which has come to be known as the Bode equalizer. The name Bode is familiar to engineers through his many other contributions to electrical engineering. The original application was for telephone carrier systems, with top frequencies of a few Megahertz or so. A number of articles have appeared in print on the subject over the years, usually related to the same frequency range. The technique is readily adaptable to the VHF range for CATV purposes, and this has been done in recent years.

Equalization

In any cable-repeater amplifier system, equalization of the cable attenuation is a fundamental requirement. For the frequencies and transmission lines of interest in CATV, the decibel attenuation is very nearly proportioned to the square root of the frequency. In order to maintain uniform signal levels over a long cascade of cable spans and repeater amplifiers, unity gain must be preserved. The repeater amplifier must complement the cable loss, i.e., the amplifier must have high gain at high frequencies and low gain at low frequencies. This can be done by arranging the active devices themselves to have the desired gain-versus-frequency characteristic. But the more common pattern nowadays is to use a more or less flat broadband amplifier with a separate passive equalizer. This equalizer is usually a bridged-T circuit, and may have any number of adjustments available to achieve system flatness.

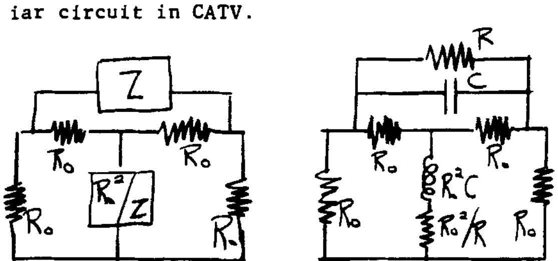
The major concern of this article is the need for variable equalization. The need arises because as the cable temperature changes, its attenuation changes, in a fashion also proportional to frequency. The normal rule of thumb is that attenuation changes by .2% per ^{o}C (.11% per ^{o}F.), at any frequency. A 22 dB span of cable at 20^{o} C will be a 23 dB span at 43^{o}C and a 21 dB span at -3^{o}C. To preserve unity gain, the corresponding amplifier must change its gain by +1 dB -1 dB at the top frequency, and by lesser amounts at lower frequencies, with the same frequency characteristic. This needs to be done automatically, simply, and reliably.

The usual passive equalizer is designed with minimum loss at the top frequency, and a variety of controls for the loss at lower frequencies. It does not lend itself well to the thermal compensation problem described above. A variety of "handles" is desirable for setting-up a system, but a simple and reliable control system for automatic operation of a number of controls is difficult to conceive, to say the least.

What is needed then is a separate network to perform the gain adjustment function. It should have a single control point, and be capable of precise gain-versus-frequency control. The Bode equalizer fills this need.

Bridged-T Networks

First a brief review of some pertinent network theory. The bridged-T network is a familiar circuit in CATV.

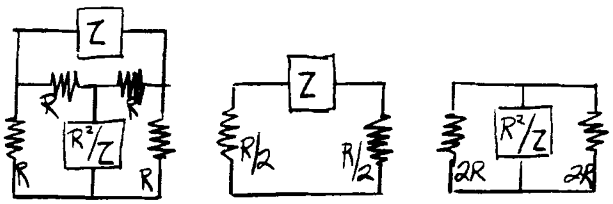


a Figure 1 b

Bridged-T Networks

Frequently used for equalizers and attenuators, it has the property of showing a purely resistive input impedance of Ro ohms if the series network and the shunt network are duals of each other, and the network is properly terminated. Referring to Figure 1a, this means that the product of the series network impedance and the shunt network impedance must equal Ro^2, and the network must be terminated with Ro. Another way of saying this is if the series network impedance is Zo, then the shunt network impedance must be Ro^2/Zo. For the usual case of Ro = 75Ω, this might be as simple as a 68Ω resistor for Zo, and an 82Ω resistor for Ro^2/Zo, in which case you would have a 5.6 dB flat pad. Figure 1b, shows a simple kind of equalizer circuit. The parallel RC network in the series leg and the series RL network in the shunt leg are duals.

It is sometimes stated that the series network controls the response of the entire bridged-T network. This is true, and can be carried even further; the series network of a bridged-T network in an Ro ohm system can be lifted out and placed in series in an Ro/2 system to yield exactly the same insertion loss characteristic. Moreover, the shunt network can be likewise taken out and placed in shunt in a 2 Ro ohm system, also with the same insertion loss.



a b c

Figure 2

Three Networks with the same Insertion Loss

Of course the new networks will not be matched; they will not have the Ro input impedance of the bridged-T circuit. But the notion is very useful for analysis and discussion, and, with due caution, for bench testing.

Another point to mention is that if the bridged-T network is not terminated in its characteristic impedance will not in general even be resistive, let alone equal to Ro.

The Bode Equalizer

The curves of Figure 3 represent a sweep system display of an equalized length of cable at three different temperatures. The coordinates are chosen to correspond to a conventional scope display. The idea here is that the cable has been perfectly equalized by a passive network at a nominal temperature. For low temperatures, the loss decreases in a manner proportional to frequency and for high temperatures the loss increases in a similar fashion.

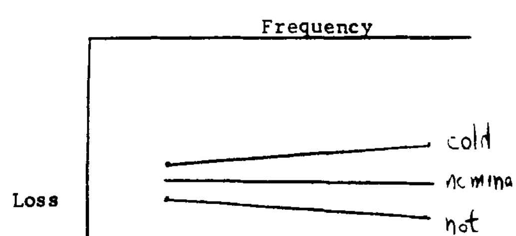


Figure 3

Loss of Equalized Length of Cable at Various Temperatures

We now look for a network capable of keeping the transmission flat across the band by some simple control. Figure 4 shows what kind of characteristics this network must have, considering only series attenuator networks, as discussed earlier. For low temperatures, a series RL network of 4a with attenuate the high frequencies more than the low, in effect simulating cable, because of the increasing reactance of the inductor with frequency. At midrange, the resistor of 4b causes flat loss. For high temperatures, the parallel RC of 4c will have less attenuation at high frequencies, due to the decreasing reactance of the capacitor, and will act like a cable equalizer.

The Bode equalizer is a circuit which will vary smoothly and controllably between the three states of Figure 4. It is itself a bridged-T circuit, with a variable termination.

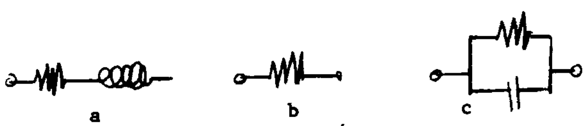


Figure 4
Desired Variable Equalizer Characteristics

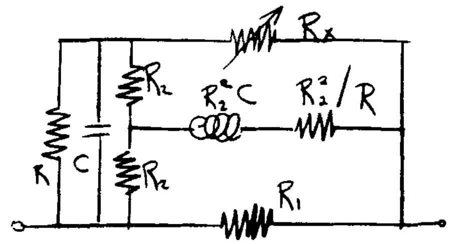


Figure 5
Bode Equalizer - Series Version

Referring to Figure 5, the parallel RC and the series RL are made to be duals of each other with respect to R_2, such that the product of their impedances is equal to R_2^2. This is similar to the network of Figure 1b. Now when this bridged-T circuit is properly terminated, i.e., when $R_x = R2$, the input impedance is equal to R2, and this is simply in parallel with R_1, and we have the condition of Figure 4b. When R_x is shorted, the parallel RC is placed across R1, yielding essentially the condition of Figure 4c. And when $R_x = \infty$, the general effect is to connect the series RL network in series in the line.

The critical point is the ability of the network to vary smoothly, predictably, and symmetrically through the three states described on Figure 4, when only the terminating resistance R_x is varied. It is the reflection coefficient of R_x with respect to R2 or $\rho = \frac{Rx - R2}{Rx + R2}$, which determines what fraction of the total range of the equalizer is brought into play. Figure 6 indicates the behavior of a Bode equalizer for various terminations.

Appendix II presents a proof that the above statements of the previous paragraph are true. The proof indicates how R_1 and R2 are to be chosen, but if one accepts on faith the symmetry property, it is not difficult to see how to pick R_1 and R_2.

Design Procedure

The starting point is the desired flat loss of the network, called on Figure 6.

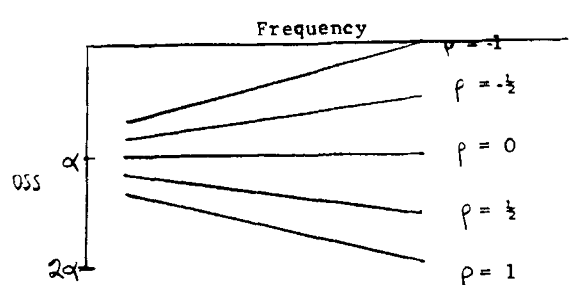


Figure 6
Loss of a Bode Equalizer

This will usually be somewhat more than half the total range of control desired. Going back to Figure 5, the equalizer will be flat when $R_x = R_2$. The input impedance to the R_2 bridged-T network will be R_2 ohms, and this will be in parallel with R_1. This establishes that R_2 in parallel with R_1 is the resistance that determines the flat loss of the Bode equalizer. Also from Figure 5 notice that for $R_x = \infty$, at very high frequencies, the series inductor takes everything out of the picture except R_1. Now back to Figure 6, and the realization that for that situation, the symmetry condition requires that R_1 be associated with 2α, twice the flat loss. In other words, if this circuit is to be symmetrical about a flat loss of α dB, then its two extremes have to be 0 dB and 2α dB.

To sum it up; pick R_1 to yield twice the desired flat loss, and pick R_2 such that $R_2 \| R_1$ yields the desired flat loss.

The more difficult part lies ahead; how to choose the reactances to yield the desired equalization. But the theory of the Bode equalizer simplifies this task enormously. With Rx set to zero, you design an equalizer by your favorite method; "tweaking" at the bench, calculating breakpoints, or computer programs. Once the equalizer is designed on a Bode basis, one can be confident that varying Rx will produce the desired symmetrical behavior. Appendix I is an example of a CAD program used to design a Bode equalizer. Of course, if we are dealing with broadband VHF, the accuracy of the final result will depend on how well the stray impedances are dealt with. And that is a significant qualification.

The equalizer based on a parallel RC described above is about as simple as possible. The need for wider bandwidth, increased precision, or wider range may require a more complex network to start with, e.g., two parallel RC's in series, or a series LC.

The Bode equalizer is by no means limited to the specific usage described above. Any variable gain versus frequency characteristic which is symmetrical about a flat loss can be accomplished this way. Figure 7 shows some of the possibilities. Figure 7a shows what is usually called a slope control, normally used to interpolate between fixed values of main equalizer for set-up purposes. Another conceivable version is shown in 7b, which is an adjustable bow or sag.

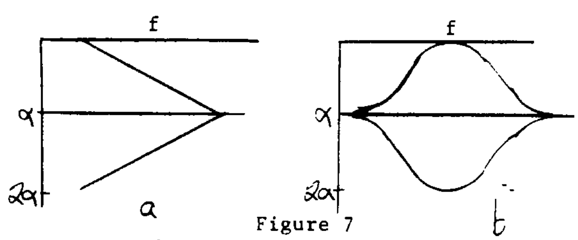


Figure 7
Other Bode Type Equalizers

To be useful in CATV, the Bode equalizer must be used in an impedance matched version. This is accomplished by providing the 75 Ω dual in the shunt position of a 75 Ω T. The dual of a bridged-T network is itself a bridged-T network. The dual of the terminating resistor must also be provided. Figure 8 shows a full dual version of the circuit of Figure 5.

In a fully matched Bode equalizer the terminating resistor must also be provided dually. There are a variety of ways of doing this. Dual potentiometers are available, but are not suitable for automatic control. PIN diodes and thermistors are candidates for R_x. The PIN diodes may be controlled by an AGC loop, or perhaps by a thermistor. One thing to keep in mind is that to achieve to full range of the Bode equalizer. R_x must vary very widely, from a short to an open circuit.

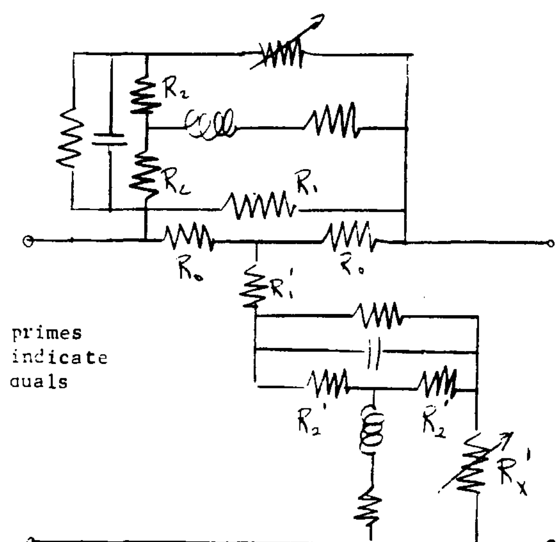


Figure 8
Full Dual Bode Equalizer

Bibliography

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Appendix I

This is a CAD program used for designing a Bode equalizer. It is written for COMPACT, a network analysis and optimization program, which is available on UCS timesharing and elsewhere. This equalizer uses two parallel RC networks in series. They are assigned in lines 100-120. In line 190 the terminating resistance is set to 10 ohms. Line 250 puts 4.5 dB of cable in series with the equalizer, and lines 290 and 320 instruct the program to look at 5 to 115 MHz, and make the total loss 5.7 dB.

```
00100 PRC AA SE  -75   -100
00110 PRC BB SE  -33   -240
00120 CAS AA BB
00130 RES BB PA  204
00140 RES CC SE  110
00150 INV DD AA  110
00160 RES EE SE  110
00170 CAX BB EE
00180 PAR AA BB
00190 SBR AA AA   10
00200 RES BB SE   75
00210 INV CC AA   75
00220 RES DD SE   75
00230 CAX BB DD
00240 PAR AA BB
00250 CAB BB SE  4.5   .05   .0007
00260 CAS AA BB
00270 PRI AA S1   75
00280 END
00290 5 115 10
00300 END
00310 0.1
00320 0 0 10 -5.7
00330 END
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