A circuit arrangement compensates for the undesired linear component of a transfer function which contains both linear and nonlinear terms. A nonlinear circuit element having a finite constant resistance is connected between the output and input of an amplifier. An input resistor determines the current conducted from a source of voltage potential to the input of the amplifier. A resistance output network is connected between the output of the amplifier and circuit ground and has a terminal which forms the output of the transfer circuit. A variable resistance network is connected between the source of voltage potential and the output of the transfer circuit. By adjusting the variable resistance network the linear term of the transfer function resulting from the finite constant resistance of the nonlinear circuit element can be eliminated to produce a pure nonlinear transfer function. Two pure nonlinear circuits are combined to form a dual channel transfer function having an output which is the difference between pure nonlinear functions of two independent variables.

13 Claims, 4 Drawing Figures

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PURE NONLINEAR TRANSFER CIRCUIT

The present invention relates to nonlinear transfer circuits and more particularly to nonlinear amplifier circuits having a pure nonlinear transfer function.

In the field of nonlinear amplifiers, it has been the general practice to employ a variety of nonlinear devices in a feedback path from the output to the input of the amplifier thereby providing a nonlinear transfer function. One of the most widely used devices for this purpose is the diode, providing a source of both square law and logarithmic functions. The base emitter voltage characteristic of a junction transistor also finds utility as a logarithmic function of the collector current. A typical circuit arrangement embodying a transistor in the feedback path of an amplifier to provide a nonlinear transfer function is that illustrated in U.S. Pat. No. 3,237,028, entitled "Logarithmic Transfer Circuit," issued Feb. 22, 1966, to J. F. Gibbons. Although such devices have served the purpose, they have not proved entirely satisfactory under all conditions of service for the reason that the voltage across the device is a linear as well as nonlinear function of the current through the device. This linear relationship is generally produced by a fixed resistance which is characteristic of most of the nonlinear devices employed. In transistors, this resistance usually results from the bulk resistance of the emitter. Considerable difficulty has been experienced with this linear resistance component in that it destroys or masks the desired nonlinear function. Further, when two or more nonlinear circuits are utilized together, such as two logarithmic circuits combined in a subtractive manner to produce the logarithm of the ratio of two variables, an undesired linear relationship makes it very difficult if not impossible to obtain the true logarithm of the ratio. Those concerned with the development of nonlinear amplifiers have long recognized the need for substantially pure nonlinear transfer functions. The present invention fulfills this need.

The general purpose of this invention is to provide a nonlinear amplifier circuit which embraces all the advantages of similarly employed nonlinear transfer circuits and possesses none of the aforesaid disadvantages. To attain this, the present invention contemplates a unique resistance circuit arrangement in the input and output of a nonlinear amplifier circuit whereby the undesired linear component of the transfer function is avoided.

An object of the present invention is the provision of a circuit transfer function having a purely nonlinear characteristic. Another object is to provide a nonlinear amplifier circuit having a pure nonlinear transfer function.

A further object of the invention is the provision of a nonlinear amplifier circuit in which the undesired linear component of the transfer function is canceled by a resistance network combining predetermined portions of the input and output of the amplifier.

Still another object is to provide a dual channel pure nonlinear transfer circuit having an output which is the difference between nonlinear functions of two independent variables.

Yet another object of the present invention is the provision of a nonlinear amplifier circuit having a transfer characteristic which is a pure logarithmic function.

A still further object is to provide a dual channel pure nonlinear transfer circuit having an output which is the logarithm of the ratio of two independent variables.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the same become better understood by reference to the following detailed description when considered in connection with the accompanying drawings in which like reference numerals designate like parts throughout the figures thereof and wherein:

FIG. 1 illustrates a nonlinear amplifier circuit employing a preferred embodiment of the invention;

FIG. 2 illustrates Fig. 1 employing several typical nonlinear elements particularly useful in the preferred embodiment of the invention; and

FIG. 4 illustrates a dual channel nonlinear amplifier configuration embodiment of the invention.

Referring now to the drawings, there is illustrated in FIG. 1 an amplifier 5 having a noninverting input 7 connected to circuit ground, an inverting input 6 and an output 8. A nonlinear device or element 9 is connected by leads or electrodes 10 and 12 to input 6 and output 8 of the amplifier, respectively. Nonlinear element 9 is of the type in which the voltage between electrodes 12 and 10 is a nonlinear function of the current through the element. Input 6 of amplifier 5 is further connected through resistor 13 to junction 14 which in turn is connected to a source of voltage potential \( V_s \). Output 8 of amplifier 5 is further connected through resistor 15 to junction 16 from which resistor 17 is connected to circuit ground. Variable resistor 18 is connected between junction 14 and junction 16 to complete the circuit.

FIGS. 2 and 3 illustrate typical nonlinear components of the type readily adapted into the circuit of FIG. 1. FIG. 2 is a typical diode having a voltage which is a logarithmic function of the current. FIG. 3 shows a transistor in which the base to emitter junction voltage is a logarithmic function of the emitter or collector current therein.

A dual channel nonlinear amplifier circuit is illustrated in FIG. 4. Two identical nonlinear amplifier circuits similar to that employed in FIG. 1, are each respectively connected to a source of voltage potential \( V_s \) and \( V_s \). Similar to FIG. 1, amplifier 5 has input 6 connected through resistor 13 to junction 14 which in turn is connected to \( V_s \). The sample channel source of voltage potential from a dual channel radiant energy analyzer. Output 8 of amplifier 5 is connected through resistor 15 to junction 16. Instead of variable resistor 18 illustrated in FIG. 1, an alternate network, connected between junctions 14 and 16, is illustrated in FIG. 4. Potentiometer 38 is connected from junction 14 to circuit ground. The variable tap of potentiometer 38 is connected through resistor 13 to junction 16.

Amplifier 25, similar to amplifier 5, has a noninverting input 27 connected to circuit ground, an inverting input 26 and an output 28. Input 26 is connected through resistor 29 to junction 30 which in turn is connected to the reference channel source of voltage potential \( V_s \) from the dual channel radiant energy analyzer. Output 28 is connected through resistor 31 to junction 32. Potentiometer 39 is connected between junction 30 and circuit ground. The variable tap of potentiometer 39 is connected through resistor 41 to junction 32.

A dual nonlinear device 19, of the type having two nonlinear elements and illustrated as a dual transistor, has a first transistor collector electrode 20 connected to input 6 and a first transistor emitter electrode 22 connected to output 8 of amplifier 5. The second transistor element of device 19 has collector electrode 23 connected to input 26 and emitter electrode 24 connected to output 28 of amplifier 25. The base electrodes 21 of the dual transistors are connected together and to circuit ground.

Junctions 32 and 16 are connected through a double pole double throw switch to noninverting input 36 and inverting input 37 of amplifier 33. The switch armatures are connected to the inputs of amplifier 33. Resistor 35 is connected from input 36 to circuit ground and resistor 35 is connected from input 37 to output 34 of amplifier 33. Output voltage \( V_{out} \) for the dual channel circuit is measured between output 34 and circuit ground.

The operation of the present invention can best be described by reference to the embodiment illustrated in FIG. 1. Since input 6 of amplifier 5 is an input circuit of the nonlinear potential by reason of input 7 being connected to circuit ground, resistor 13 determines a current \( i_s \) from voltage potential \( V_s \). This \( i_s \) is conducted through nonlinear element 9 to produce a voltage at output 8 of \( V'_{out} \). If, for example, nonlinear element 9 is a transistor as illustrated in FIG. 3, \( V'_{out} \) will contain both a linear and nonlinear function of the current \( i_s \). This relation is illustrated in the following equation:

\[
V'_{out} = -V_{be}(i_s) - i_sR_{ee}
\]
where \(-V_{\text{out}}(i)\) is a pure nonlinear function and \(iR_{\text{re}}\) is the undesired linear function, \(R_{\text{b}}\) being the bulk resistance of the emitter. Therefore, it is clear that if the output of the nonlinear amplifier circuit were taken from output 8, both the nonlinear relationship \(V_{\text{out}}(i)\) and the linear function \(iR_{\text{re}}\) appear. Since a voltage which is a linear function of \(i\) is present at output 8, such a nonlinear device having a fixed nonlinear resistance does not provide a pure nonlinear transfer characteristic for the amplifier circuit. Now the present invention combines the linear function can be illustrated by solving for the voltage potential \(V_{\text{out}}\) appearing at junction 16 with respect to circuit ground. The sum of the currents entering and leaving junction 16 is as follows:

\[
\frac{V_{n}(i) - V_{\text{out}}(i)}{R_{15}} + \frac{V_{n}(i) - V_{3}}{R_{18}} + \frac{V_{n}^{a}}{R_{17}} = 0
\]

(2)

where the numbers refer to the designation of the resistance elements in the drawings. Collecting terms in equation (2),

\[
V_{n}\left(\frac{1}{R_{15}} + \frac{1}{R_{18}} + \frac{1}{R_{17}}\right) = \frac{V_{\text{out}}(i) - iR_{\text{re}}}{R_{15}}
\]

(3)

Noting that \(V_{n} = R_{15}i\), and substituting for \(V_{\text{out}}(i)\) from equation (1) and for \(i\),

\[
\frac{1}{R_{15}} + \frac{1}{R_{18}} + \frac{1}{R_{17}}
\]

(4)

Since it is desired that there be no linear term in the equation, \(R_{18}\) is adjusted such that

\[
iR_{\text{re}} = R_{15}i\]

or

\[
R_{18} = R_{25}R_{15}
\]

(5)

Therefore, solving for \(V_{n}\),

\[
V_{n} = -\frac{V_{\text{out}}(i)}{\frac{1}{R_{15}} + \frac{1}{R_{18}} + \frac{1}{R_{17}}}
\]

(6)

Therefore it is clear from the equations set forth above that any linear resistance which produces a voltage linearly related to the current through the nonlinear element, is canceled at junction 16 by adjusting resistance 18 to be equal to the product of resistance 13 and resistance 15 divided by the linear resistance of the nonlinear element.

Referring now to the operation of the circuit illustrated in FIG. 4, let the position of the double pole double throw switch at the input to amplifier 33 be in a first position such that input 36 is connected to junction 16 and input 37 is connected to junction 32. The nodal equation for junction 16 is

\[
\frac{V_{n} - V_{\text{out}}(i)}{R_{40}} + \frac{V_{n}(i) - V_{\text{out}}(i)}{R_{15}} + \frac{V_{n}^{a}}{R_{17}} = 0
\]

(8)

where \(K_{i}\) is the fraction which represents that portion of \(V_{n}\) which appears at the variable tap of potentiometer 38 with respect to ground, \(V_{n}\) is the voltage at junction 16 and \(V_{\text{out}}(i)\) is the voltage at output 8 of amplifier 5. Noting that \(V_{\text{out}}(i) = V_{\text{out}}(i), iR_{\text{re}}\), where \(iR_{\text{re}}\) is the current through junction 15, substituting for \(iR_{\text{re}}\) and collecting terms,

\[
V_{n}\left(\frac{1}{R_{40}} + \frac{1}{R_{15}} + \frac{1}{R_{17}}\right) = K_{i}V_{n}^{a} + \frac{V_{\text{out}}(i)}{R_{15}} + \frac{V_{\text{out}}(i)}{R_{17}}
\]

(9)

Similar to the equations developed for the circuit of FIG. 1, by letting \(R_{15}R_{40} = R - R_{25}R_{15}\), the transfer function is adjusted to be purely nonlinear. Therefore, the voltage at junction 16 with respect to ground is

\[
V_{n} = \frac{V_{\text{out}}(i)}{R_{15}}\left(\frac{1}{R_{40}} + \frac{1}{R_{15}} + \frac{1}{R_{17}}\right)
\]

(10)

Since the inverting input 37 of amplifier 33 is essentially at the same potential as the noninverting input 36, the nodal equation for junction 32 can be written as follows:

\[
\frac{V_{n}(i) - V_{\text{out}}(i)}{R_{40}} + \frac{V_{n}^{a}}{R_{17}} = 0
\]

(11)

where \(K_{i}\) is the fraction of \(V_{n}\) appearing at the adjustable tap of potentiometer 39 with respect to circuit ground and \(V_{\text{out}}(i)\) is the voltage at output 28 of amplifier 25. Noting that

\[
V_{\text{out}}(i) = -V_{\text{out}}(i) + V_{\text{out}}(i)
\]

(12)

where \(i\) is the current in resistor, substituting in equation (11) for \(V_{\text{out}}(i)\) from equation (12) and collecting terms,

\[
V_{n}\left(\frac{1}{R_{40}} + \frac{1}{R_{15}} + \frac{1}{R_{17}}\right) = K_{i}V_{n}^{a} + \frac{V_{\text{out}}(i)}{R_{15}} + \frac{V_{\text{out}}(i)}{R_{17}}
\]

(13)

Cancelling out the linear components of the transfer function by adjusting \(R_{15}/K_{i}\) to equal \(R_{25}R_{15}/R_{17}\), then

\[
V_{n}\left(\frac{1}{R_{40}} + \frac{1}{R_{15}} + \frac{1}{R_{17}}\right) = V_{\text{out}}(i) + R_{15}
\]

(14)

Substituting in equation (14) for \(V_{n}\) from equation (10) and solving for \(V_{\text{out}}(i)\),

\[
V_{\text{out}}(i) = \frac{V_{\text{out}}(i) + \frac{R_{15} + R_{17}}{R_{15}}}{R_{15}}
\]

(15)

By selecting the values of the resistances to be equal in similar circuit positions in amplifier 5 and amplifier 25 and by letting the ratio of \(R_{25}/R_{15}\) equal \(a\), \(V_{\text{out}}(i)\) can be written as

\[
V_{\text{out}}(i) = \frac{aR_{15}}{R_{15}}V_{\text{out}}(i) + V_{\text{out}}(i)
\]

(16)

Since \(V_{\text{out}}(i)\) and \(V_{\text{out}}(i)\) represent the true junction voltages of the emitter base junctions of the dual transistor 19 and no emitter bulk resistance \(R_{15}\) and \(R_{17}\), \(V_{\text{out}}(i)\) and \(V_{\text{out}}(i)\) can be written as

\[
\frac{V_{\text{out}}(i)}{q} = \frac{K_{T}T^{2}}{q}
\]

(17)

and

\[
\frac{V_{\text{out}}(i)}{q} = \frac{K_{T}T^{2}}{q}
\]

(18)

where \(K_{T}\) is Boltzmann's constant, \(T\) is absolute temperature, \(q\) is the charge of an electron and \(h\) is the natural logarithm.

Therefore, substituting equations (17) and (18) in equation (16), \(V_{\text{out}}(i)\) can be written

\[
V_{\text{out}}(i) = b - \frac{h}{q}
\]

(19)

where \(b\) equals \(aK_{T}T^{2}\). Collecting terms in equation (19),

\[
V_{\text{out}}(i) = b - \frac{h}{q}
\]

(20)

It should be clear that \(V_{\text{out}}(i)\) can also be written as

\[
V_{\text{out}} = b - \frac{h}{q}
\]

(21)

since \(R_{15}\) is adjusted to be equal to \(R_{25}\). Therefore, the circuit of FIG. 4 provides an output voltage which is proportional to the logarithm of the ratio of two input voltage potentials \(V_{n}\) and \(V_{n}\) which may be the output of a dual channel radiant energy analyzer. By appropriate adjustment of potentiometers 38 and 39, the output of the dual channel nonlinear transfer circuit is purely nonlinear. It should also be clear that by placing the double pole double throw switch in a second position, connecting input 36 to junction 32 and input 37 to junction 16, the ratio of \(V_{n}/\overline{V}_{n}\) is inverted, thereby giving

\[
V_{\text{out}} = b - \frac{h}{q}
\]

(22)

In order for the temperature \(T\) to be the same in both expressions (17) and (18) for \(V_{\text{out}}(i)\) and \(V_{\text{out}}(i)\), dual transistors mounted on the same substrate and in the same package are employed.
It now should be apparent that the present invention provides a circuit arrangement which may be employed in conjunction with a nonlinear amplifier for cancelling unwanted linear components of the nonlinear transfer function by introducing a certain amount of the unwanted linear signal into the amplifier output with proper phase and amplitude such that no unwanted linear signal appears at the output of the nonlinear amplifier. The present invention also provides a circuit arrangement which may be employed in conjunction with a dual channel radiant energy analyzer for providing a pure logarithmic ratio of one channel voltage potential to the other. Although particular components have been discussed in connection with a specific embodiment of a circuit constructed in accordance with the teachings of the present invention, others may be utilized. Furthermore, it will be understood that although an exemplary embodiment of the present invention has been disclosed and discussed, other applications and circuit arrangements are possible and that the embodiments disclosed may be subjected to various changes, modifications and substitutions without necessarily departing from the spirit of the invention.

What is claimed is:

1. A transfer circuit of the type having a nonlinear circuit element connected between the output and input of an amplifier wherein the voltage across the element can be related to a nonlinear and a linear function of the current therethrough and wherein the input of the amplifier is further connected through an input resistor to a source of input signal voltage, the improvement comprising:
a resistance output network having at least three terminals of which a first terminal is connected to the output of the amplifier, a second terminal is connected to circuit ground, and a third terminal forms the output of the transfer circuit, having a pair of impedance elements connected in series between said first and second terminals, the junction between said elements forming said third terminal; and
a variable resistance network connected between the source of input voltage and said resistance output network third terminal for adjusting the voltage at said output of the transfer circuit to be proportional only to the nonlinear function of current in the nonlinear circuit element.

2. The transfer circuit improvement described in claim 1 wherein said impedance elements are resistive.

3. The transfer circuit improvement described in claim 2 wherein said variable resistance network includes a potentiometer having its variable tap connected to one end thereof forming a variable resistance connected between the source of input signal voltage and said third terminal.

4. The transfer circuit improvement described in claim 2 wherein said variable resistance network includes:
a potentiometer connected between the source of input signal voltage and circuit ground, the variable tap thereof providing a source of adjustable input signal voltage; and
a resistor connected between said variable tap and said third terminal.

5. The transfer circuit improvement described in claim 3 wherein the nonlinear circuit element is a diode.

6. The transfer circuit improvement described in claim 3 wherein the nonlinear circuit element is a transistor, the base electrode being connected to circuit ground and wherein the nonlinear function is the logarithmic relation between junction voltage and current.

7. In a radiant energy analyzer of the type having sample and reference channel signals, a dual channel nonlinear transfer circuit for determining the difference between nonlinear functions of the sample and reference signal, comprising:
first and second amplifier means, each having an input and an output;
first and second input resistors, said first input resistor being connected between said first amplifier means input and a first voltage potential proportional to the magnitude of the sample signal and said second input resistor being connected between said second amplifier means input and a second voltage potential proportional to the magnitude of the reference signal, said first and second input resistors determining the current to said first and second amplifier means, respectively;
first and second nonlinear elements, each having a voltage represented by the combination of a nonlinear and a linear function of the current therethrough, said first and second nonlinear elements being connected between said input and output of said first and second amplifier means, respectively, whereby said input current to said first and second amplifier means is conducted through said first and second elements, respectively;
and
first and second output resistors having one end thereof connected to said output of said first and second amplifier means, respectively;
a first resistance network having a first terminal connected to said first voltage potential and a second terminal connected to the other end of said first output resistor;
a third amplifier means having an output and a pair of inputs, one input of said pair being connected to the junction of said first network and said first output resistor and the other input of said pair being connected to the other end of said second output resistor, the current to said third amplifier means one input being adjusted by said first network means to contain only a component which is a nonlinear function of said first voltage potential, said third amplifier means output having a voltage potential proportional to the difference of said nonlinear function of said first voltage potential and said linear and nonlinear function of said second voltage potential.

8. The dual channel transfer circuit described in claim 7 further including a second resistance network having a first terminal connected to said second voltage potential and a second terminal connected to the junction of said second output resistor and said third amplifier means other input, the current to said third amplifier means other input being adjusted by said second network to contain only a component which is a nonlinear function of said second voltage potential whereby said third amplifier means output voltage potential is the difference of said nonlinear function of said first voltage potential and said nonlinear function of said second voltage potential.

9. The dual channel transfer circuit described in claim 8 wherein said third amplifier means comprises:
an operational amplifier having an inverting and noninverting input and an output;
a first resistor connected between said noninverting input and circuit ground; and
a feedback resistor connected between said inverting input and said output of said operational amplifier.

10. The dual channel transfer circuit described in claim 9 further including switching means having at least two switch positions for connecting said operational amplifier noninverting input to said junction of said first network and said first output resistor and connecting said inverting input to the junction of said second network and said second output resistor when said switching means is in a first position and for interchanging said operational amplifier input connections when in a second position.

11. The dual channel transfer circuit of claim 9 wherein first and second resistance networks each comprise a potentiometer connected as a variable resistor.

12. The dual channel transfer circuit of claim 9 wherein said first and second resistance networks each comprise:
a potentiometer connected between circuit ground and said first terminal; and
a resistor connected between the variable tap of said potentiometer and said second terminal.

13. The dual channel transfer circuit of claim 9 wherein said first and second nonlinear elements are transistors having the base electrodes thereof connected to circuit ground.