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(54) IMPROVEMENTS IN OR RELATING TO FILTER CIRCUITS

(71) We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 195, Broadway, New York City, New York State, United States of America, a Corporation organised and existing under the laws of the State of New York, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement: —

This invention relates to filter circuits.

The development of integrated circuits has engendered considerable interest in the field of active RC, i.e., resistor-capacitor, circuits. As the name implies, an active RC circuit is one composed solely of resistors, capacitors, and some form of active element, e.g., an amplifier. Since such circuits do not use inductors, they find application where weight and size must be minimized. Furthermore, other problems associated with inductors are eliminated, e.g., problems arising from the magnetic fields and nonlinear behavior of inductors. In addition, RC active circuits are particularly advantageous in integrated form where, in general, the provision of inductors is not feasible.

Numerous circuits have been used to provide biquadratic (second-order) active filter sections. Various criteria have guided design of such circuits including miniaturization, economy, simplicity, low characteristic variability, realization in cationic form, etc. Many of these circuits, although complying with some of the mentioned criteria, are extremely complex, requiring many components and expensive active elements, or are highly sensitive to parameter changes in the various elements of which they are comprised.

This invention seeks to provide improved filter circuits.

According to this invention a filter circuit includes an amplifier having first and second input terminals and having an output terminal common with the filter circuit output terminal, a first resistor connected between said first amplifier input terminal and said filter circuit output terminal, a second resistor having one terminal connected to the input terminal of said filter circuit and its other terminal connected to one terminal of a first capacitor and the other terminal of which is connected to said first amplifier input terminal, a third resistor connected between said second amplifier input terminal and a terminal of fixed potential, a fourth resistor connected between said second amplifier input terminal and said filter circuit output terminal, a second capacitor connected between the common connection of said second resistor and said first capacitor and said filter circuit output terminal, and a fifth resistor connected between said common connection and said terminal of fixed potential.

The invention will now be described with reference to the accompanying drawing, in which:

FIG. 1 is a schematic circuit diagram of a general second-order filter section in accordance with the invention;

FIG. 2 is the electrical equivalent of the circuit of FIG. 1;

FIG. 3 is a schematic circuit diagram of a modified version of the filter of FIG. 1 which exhibits a bandpass transfer function;

FIG. 4 is a schematic circuit diagram of the circuit of FIG. 1 modified to exhibit a high-pass or a high-pass notch filter transfer function; and

FIG. 5 is a schematic circuit diagram of the circuit of FIG. 1 modified to exhibit a low-pass notch filter transfer function;

The filter circuit of FIG. 1 includes an operational amplifier 11, having differential input terminals 12 and 13, and a gain A_o. Two resistors 14 and 15 shunt amplifiers 11 and are connected, respectively, between amplifier input terminals 12 and 13 and amplifier output terminal 16, which also serves as the output terminal of the complete filter circuit. Connected between a fixed potential common lead 17, e.g., ground, and amplifier input terminals 12 and 13, respectively, are resistors 18 and 19. Capacitors 21 and 22 are serially connected between output terminal 16 and amplifier input terminal 12. Connected to the common terminal junction of capacitors 21 and 22 are resistors 24 and 25, the other terminal of resistor 25 being connected to common lead 17 and the other terminal of resistor 24 being connected to circuit input terminal 26. Resistors 27 and 28 are connected between input terminal 26 and amplifier terminals 13 and 12, respectively. The values of the various resistors depicted in FIG. 1 are identified in terms of conductance, i.e., the reciprocal of resistance, for example, G_a, G_b, etc.; the capacitive values of capacitors 22 and 21 are C_1 and C_2, respectively.

For explanatory purposes, an equivalent circuit to that of FIG. 1 using ideal current sources 31, 33 and 35 is shown in FIG. 2.

The relationship between the various parameters of the circuits of FIG. 1 and FIG. 2 are given by the following expressions:

$$G_a = G_c + G_d$$

$$G_1 = G_4 + G_5$$

$$G_3 = G_6 + G_7$$

$$K_a = G_c/G_1$$

$$K_1 = G_4/G_1$$

$$K_2 = G_6/G_3. \qquad (1)$$

The transfer function of the circuit of FIG. 1 may be shown to be:

$$\frac{e_o}{e_s} = \frac{\left\{\begin{array}{l} C_1C_2G_aK_as^2 + \left[C_1G_aK_a\ (G_2+G_3+G_1)+C_2G_aK_a(G_2+G_3)\right] \\ -C_1G_1K_1(G_a+G_b) - (C_1+C_2)G_3K_2(G_a+G_b)\big] s \\ +G_1G_aK_a(G_2+G_3) - G_1G_3K_2(G_a+G_b) \end{array}\right\}}{\left\{\begin{array}{l} \left[C_1C_2G_a + \frac{C_1C_2\ (G_a+G_b)}{A_o}\right] s^2 + \left[(C_1+C_2)(G_aG_2-G_bG_3)\right. \\ -G_1G_1G_b + \frac{(C_1+C_2)}{A_o}\ (G_a+G_b)(G_2+G_3) + \frac{C_1}{A_o}G_1(G_a+G_b)\big] s \\ +G_1\ (G_aG_2-G_bG_3) + \frac{G_1}{A_o}(G_2+G_3)(G_a+G_b) \end{array}\right\}} \qquad (2)$$

Assuming the gain A_o of amplifier 11 to be infinite, (a common assumption when operational amplifiers are used) the transfer function of Eq. (2) may be expressed as:

$$\frac{e_o}{e_s} = \frac{K_as^2 + Es + D}{s^2 + As + B} \quad (0 \le K_a \le 1) \qquad (3)$$

Where

$$A = \frac{(C_1+C_2)(G_aG_2-G_bG_3) - C_1G_1G_b}{C_1C_2G_a} \qquad (4)$$

$$B = \frac{G_1(G_aG_2-G_bG_3)}{C_1C_2G_a} \qquad (5)$$

$$D = \frac{G_1G_aK_a(G_2+G_3) - G_1G_3K_2(G_a+G_b)}{C_1C_2G_a} \qquad (6)$$

$$E = \frac{\left\{\begin{array}{l} C_1G_aK_a(G_1+G_2+G_3) + C_2G_aK_a(G_2+G_3) \\ -C_1G_1K_1(G_a+G_b) - (C_1+C_2)G_3K_2(G_a+G_b) \end{array}\right\}}{C_1C_2G_a} \quad (7)$$

To facilitate the design of a desired filter section, Equs. (3) to (7) may be solved to develop the following equations:

$$G_1 = \frac{C_2G_a}{2G_b}\left[-A + \left(A^2 + 4\left(1+\frac{C_1}{C_2}\right)B\,\frac{G_b}{G_a}\right)^{1/2}\right] \quad (7a)$$

$$K_1 = \frac{K_a + \left(1+\frac{C_1}{C_2}\right)D\,\frac{G_2^2}{G_1^2} - E\,\frac{C_2}{G_1}}{1+\frac{G_b}{G_a}} \quad (7b)$$

$$G_3 = \frac{C_1C_2G_aB\left(\frac{D}{B}-K_a\right)}{G_1(G_a+G_b)(K_a-K_2)} \quad (7c)$$

$$G_2 = \frac{C_1C_2B}{G_1} + \frac{G_bG_3}{G_a} \quad (7d)$$

The parameters for these equations are the coefficients of the transfer function, i.e., A, B, D, E, and K_a, of Eq. (3) and circuit element values C_1, C_2, G_a, and G_b, which are arbitrarily selected. Parameter K_2 is chosen to be either 0 or 1 in Eq. (7c) to provide a minimum positive value for G_3, since a large value for parameter G_3 degrades the circuit's sensitivity performance. Once having selected the values for G_1, K_1, K_2, G_3, and G_2, the remaining element values of the circuit of FIG. 1 are determined readily from Eq. (1).

The circuit depicted in FIG. 1, and described by the above equations, may readily be altered to obtain a wide variety of diverse filter transfer functions. For example, the circuit depicted in FIG. 3 exhibits a bandpass filter transfer function by the following expression:

$$\frac{e_o}{e_s} = \frac{Es}{s^2+As+B} \quad (8)$$

This circuit is substantially the same as that of FIG. 1 but has been simply altered by the deletion of resistors 27, 28, and 18. Of course, where a resistor is deleted, here, and in the following cases, the conductive value of the deleted resistor should be set equal to zero in the relevant equations.

In determining the circuit element values for the desired filter bandpass transfer function, the value of E in Eq. (7b) must be inserted as a negative quantity to provide a positive value for K_1. Furthermore, since an indeterminate relationship arises in the case of Eq. (7c), the value of G_3 may be made equal to zero, thereby eliminating a resistor and improving pole sensitivity. Peak gain is attained when K_1 is equal to unity.

The circuit of FIG. 4, differing from that of FIG. 1 only by the absence of resistor 18, exhibits a high-pass filter transfer function given by the following expression:

$$\frac{e_o}{e_s} = \frac{K_as^2}{s^2+As+B} \quad (9)$$

For this case, i.e., the high-pass filter transfer function, the solution of Eq. (7c) poses a problem since $D=0$, and K_a being unequal to zero, the numerator is necessarily negative. Therefore, K_2 must be greater than K_a and may appropriately be made equal to unity to provide a suitable value for G_3.

In the circuit of FIG. 5, resistor 28 of FIG. 1 has been deleted. The resultant circuit has a low-pass notch filter transfer function defined by Eq. (3) with coefficient E generally made equal to zero. The low-pass notch filter is further characterized as having a D.C. gain which is greater than the gain at infinite frequency. Accord-

ingly, in terms of the parameters of Eq. (3), coefficient K_a should be less than the ratio of coefficient D to coefficient B. Parameter K_2 may conveniently be set equal to zero, thereby assuring a positive and minimum value for G_3.

Contrarily, a high-pass notch filter is characterized as having a D.C. gain which is less than the gain of the filter at infinite frequency, i.e., coefficient K_a is greater than the ratio of coefficient D to coefficient B. The structure of a circuit exhibiting such a characteristic is identical to that of FIG. 4. For this case, to assure a positive and minimum value for G_3, K_2 should be set equal to unity.

An exemplary bandpass filter, as illustrated by FIG. 3, having a Q of 80 at a frequency of 1 KHz and with a peak gain of 10 performed satisfactorily by using circuit elements having the values listed in Table I.

TABLE I

C_1=0.005 μf
C_2=0.05 μf
$1/G_2$=254.6K ohms
$1/G_4$=25.86K ohms
$1/G_5$=404.1 ohms
$1/G_b$=12.8K ohms
$1/G_d$=200. ohms

Having regard to the provisions of Section 9 of the Patents Act, attention is directed to the claims of our Patent No. 1227105.

WHAT WE CLAIM IS:—

1. A filter circuit including an amplifier having first and second input terminals and having an output terminal common with the filter circuit output terminal, a first resistor connected between said first amplifier input terminal and said filter circuit output terminal, a second resistor having one terminal connected to the input terminal of said filter circuit and its other terminal connected to one terminal of a first capacitor the other terminal of which is connected to said first amplifier input terminal, a third resistor connected between said second amplifier input terminal and a terminal of fixed potential, a fourth resistor connected between said second amplifier input terminal and said filter circuit output terminal, a second capacitor connected between the common connection of said second resistor and said first capacitor and said filter circuit output terminal, and a fifth resistor connected between said common connection and said terminal of fixed potential.

2. A circuit as claimed in claim 1 including a sixth resistor connected between said filter circuit input terminal and said second amplifier input terminal.

3. A circuit as claimed in claim 2 including a seventh resistor connected between said filter circuit input terminal and said first amplifier input terminal.

4. A circuit as claimed in claim 2 or 3 including an eighth resistor connected between said first amplifier input terminal and said terminal of fixed potential.

5. A filter circuit arranged and adapted to operate substantially as herein described with reference to FIG. 1 and 2, or with reference to FIGS. 1 and 2 as modified by FIG. 3, 4 or 5 of the accompanying drawing.

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