Second order ARC filters using transconductance amplifiers and voltage buffers for high-frequency applications

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Abstract: - Active RC second order filters using transconductance amplifier (diamond transistors, voltage controlled current sources) and voltage buffers (voltage controlled voltage sources) are given in this paper. Circuits are simulated and experimentally compared.

Key-Words: - ARC filter, transconductance amplifier, voltage buffer, diamond transistor.

1 Introduction

Recently high-frequency continuous-time ARC filters have received great attention. A progress of the analogue technology has produced several functional blocks and monolithic IC components versatile and suitable for video and RF ranges. One from them is diamond transistor OPA660 from Burr-Brown company [1]. Similar is LM13700 from National semiconductor [4]. The both IC include two wideband subcircuits, namely an operational transconductance (transadmittance) amplifier (OTA-Y) and a voltage buffer (VB). These blocks share common supplies but otherwise operate independently. The OTA-Y can be viewed as an ideal transistor, with only one parameter, what is a transconductance, that is a reason of the name in [2] a diamond transistor. There the transconductance (g_T) can be adjusted with external current (I_Q), to give possibility of tuning or optimising the parameters of the filter. Similarly the VB has the structure of the so-called diamond buffer (push-pull buffer) too [2]. The VB can be modeled by the VCVS, with *A=1*, and the OTA-Y by the VCCS respectively.

2 Simple biquadratic structure

Active RC filters are usually designed with standard operational amplifiers, however in low-frequency (audio) range only. The well known classical ARC filters can not be straightforward used for the OPA660. One ingenious modification of the Sallen-Key low-pass (LP) filter was given in [3], where the OPA660 was used as a current-feedback amplifier. There a 2-nd order RC structure is given and studied, using both functional blocks above (OTA-Y, VB).

Simple autonomous general structure based on single OTA-Y & VB is given in Fig. 1. The characteristic equation for this circuit has the following form

$$D_1 = Y_1 Y_2 + Y_1 Y_3 - g_2 = 0\,, \qquad (1)$$

The eq. (1) can be taken as a base for our synthesis. Choosing

$$Y_1 = pC_1 + G_1,\quad Y_2 = pC_2,\quad Y_3 = G_2, \qquad (2)$$

the desired second order polynomial and structure is obtained, namely

$$D_2(s) = s^2 C_1 C_2 + p[C_1 G_2 + C_2 (G_1 - g)] + G_1 G_2\,. \qquad (3)$$

From the eq. (3) the pole frequency (4) and quality factor (5) can be written in terms of the network parameters as

$$w_o = \frac{1}{\sqrt{C_1 C_2 R_1 R_2}}\,, \qquad (4)$$

and

$$Q = \frac{\sqrt{C_1 G_1 C_2 G_2}}{C_1 G_2 + C_2 (G_1 - g)}\,. \qquad (5)$$

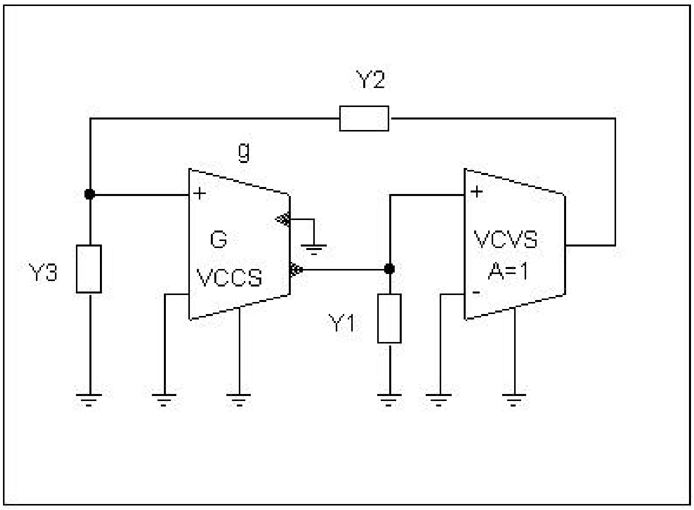

Fig. 1. Simple structure based on single OTA-Y & VB.

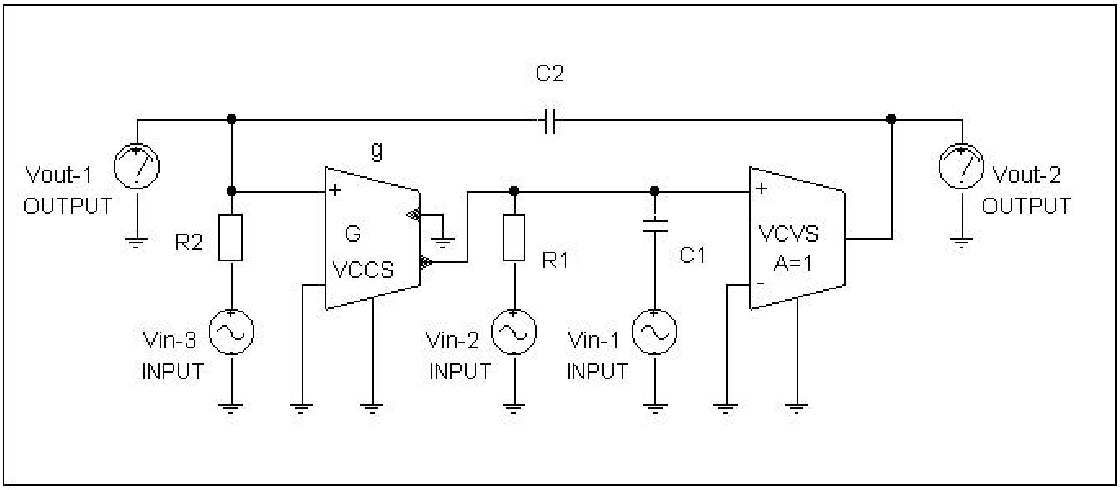

Fig. 2. Single OTA-Y & VB structure used as a 2-nd order multifunctional filter.

It is noted from (5), the Q-factor can be easy adjusted by transconductance (g). If $Q \to \infty$, the circuit will be oscillating at the frequency given by (4). Putting the denominator of (5) equal to zero a condition of oscillation is obtained as

$$g = g_o = G_1 + G_2 \frac{C_1}{C_2} \tag{6}$$

Furthermore, for $g < g_o$ the structure can be used as a ARC filter. The OTA-Y & VB based structure as a multifunctional biquad is shown in Fig. 2.

There is for $V_{in2} = V_{in3} = 0$ (short circuits) a voltage transfer function of the high-pass type

$$K_{V1} = \frac{V_{out1}}{V_{in1}} = \frac{s^2 C_1 C_2}{D_2(s)}, \tag{7}$$

Similarly if $V_{in1} = V_{in2} = 0$, the low-pass type will be

$$K_{V2} = \frac{V_{out2}}{V_{in1}} = \frac{gG_2}{D_2(s)} \tag{8}$$

The band-pass filter, with the following transfer function

$$K_{V3} = \frac{V_{out1}}{V_{in2}} = \frac{sC_2 G_1}{D_2(s)}, \tag{9}$$

is obtained taking $V_{in1} = V_{in3} = 0$.

If $V_{in3} = 0$ and $V_{in1} = V_{in2} = V_{in}$ (connecting together these inputs), the transfer function will be in this form

$$K_{V1} = \frac{V_{out1}}{V_{in1}} = \frac{s^2 C_1 C_2}{D_2(s)}, \tag{10}$$

Note that the filter (Fig. 2) can be modified in current mode too, using known adjoit transformation [5].

3 ARC biquad with current feedback

Other suitable structure of the 2-nd order ARC filter with the given functional blocks, namely with two VB (VCVS) and one OTA-Y (VCCS) and using a current feedback (R_1), mentioned in [3], is shown in Fig. 3.

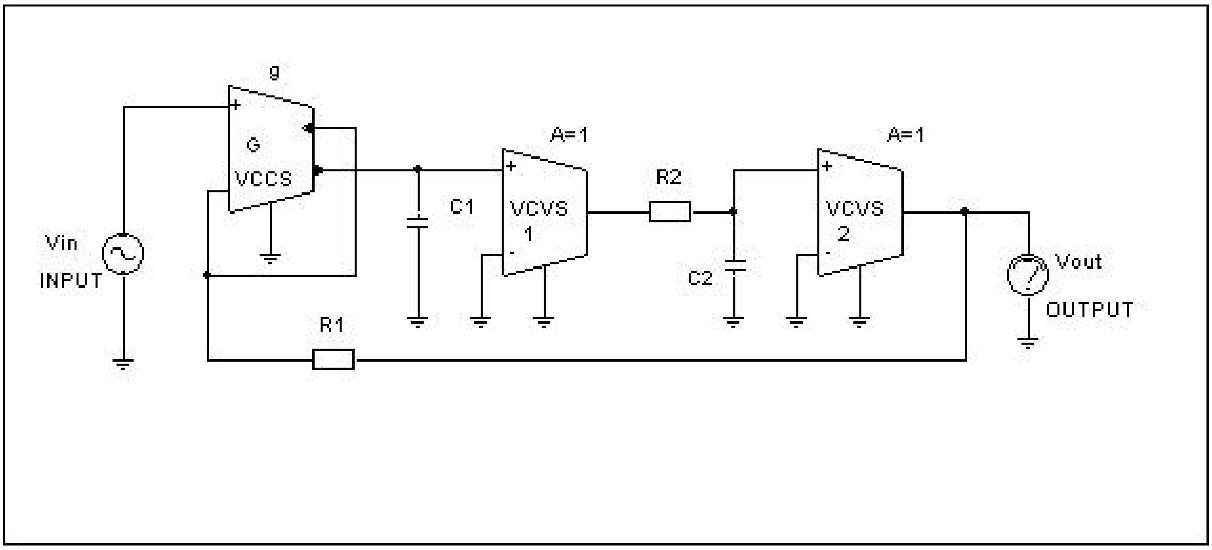

Fig. 3. Low-pass 2-nd order ARC filter using OTA-Y, two VB and current feedback.

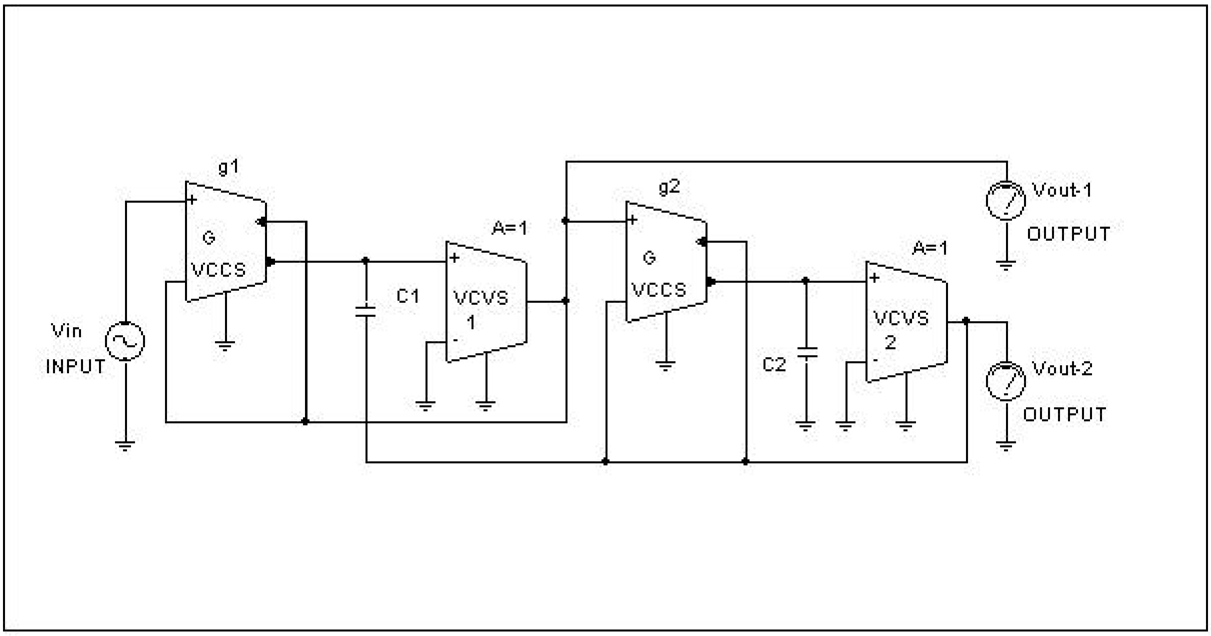

Fig. 4. Multifunctional ARC biquad structure (LP, ELP, BP, HP) using two OTA-Y & VB.

By a routine symbolical nodal analysis, doing by computer tool SNAP, the transfer function results in this form

$$\frac{V_{out}}{V_{in}} = \frac{g_1}{s^2 C_1 C_2 R_2 (1 - g_1 R_1) + sC_1 (1 - g_1 R_1) + g_1}, \quad (11)$$

visibly with the character of the low-pass filter.

Assuming a full current feedback ($R_1 = 0$), the transfer function (10) becomes simpler

$$\frac{V_{out}}{V_{in}} = \frac{g_1}{s^2 C_1 C_2 R_2 + sC_1 + g_1}. \quad (12)$$

From the above function (12), the natural frequency (13) and the quality factor of the poles (14) are

$$w_o = \sqrt{\frac{g_1}{C_1 C_2 R_2}}, \quad (13)$$

$$Q = \sqrt{\frac{C_2 g_1 R_2}{C_1}}. \quad (14)$$

Thus both parameters are controlled by the transconductance (g_1) of the OTA-Y, but not independently. Note that the desired quality factor can be adjusted by ratio of the capacitances.

There, in Fig. 3, the first voltage buffer (VCVS1) can be omitted and replaced by short circuit, to obtain the following transfer function

$$\frac{V_{out}}{V_{in}} = \frac{g_1}{s^2 C_1 C_2 R_2 + s(C_1 + C_2) + g_1}. \quad (15)$$

Then the natural frequency is at the same formula (13), however the quality factor is now given by

$$Q = \frac{\sqrt{C_1 C_2 g_1 R_2}}{C_1 + C_2}. \quad (16)$$

4 Versatile ARC biquad structure

Another structure, little complicated, but more versatile, is shown in Fig. 4. For the output V_{out2} of this circuit (Fig. 4), the voltage transfer function can be derived in the following symbolic (LP) form

$$\frac{V_{out2}}{V_{in}} = \frac{g_1 g_2}{s^2 C_1 C_2 + sC_2 g_1 + g_1 g_2}. \quad (17)$$

From the eq. (17) the pole frequency (18) and quality factor (19) are written in terms of the network parameters as

$$w_0 = \sqrt{\frac{g_1 g_2}{C_1 C_2}}, \quad (18)$$

$$Q = \sqrt{\frac{C_1 g_2}{C_2 g_1}}. \quad (19)$$

If the gain of the voltage buffers (VCVS) is not exactly equal one, then the transfer function is

$$\frac{V_{out2}}{V_{in}} = \frac{A_1 A_2 g_1 g_2}{s^2 C_1 C_2 + s(A_1 g_1 C_2 + A_2 g_2 C_1 - A_1 A_2 g_2 C_1) + A_1 A_2 g_1 g_2} \quad (20)$$

what allows to evaluate the corresponding mistakes.

The signal at the output V_{out1} (Fig. 4) is given by

$$\frac{V_{out1}}{V_{in}} = \frac{g_1 g_2 + sC_2 g_1}{s^2 C_1 C_2 + sC_2 g_1 + g_1 g_2}. \quad (21)$$

It can be used with V_{out2} in other follower, with differential input, to obtain

$$V_{out3} = V_{out1} - V_{out2}. \quad (22)$$

Then the transfer function has the band-pass character of the resultant formula

$$\frac{V_{out\,3}}{V_{in}} = \frac{sC_2 g_1}{s^2 C_1 C_2 + sC_2 g_1 + g_1 g_2}\,. \qquad (23)$$

Similarly the high-pass biquad can be obtained modifying the configuration of the adder, realising the equation

$$V_{out4} = V_{in} - V_{out1}. \qquad (24)$$

5 ARC biquad with two loop feedback

The concluding structure with two fuctional blocks OTA-Y & VB and an adder ($V_{out1} + V_{out2}$), in two loop feedback, is shown in Fig. 5. There, for the output V_{out1} the voltage transfer function has the form of the BP given by eq. (23) and for the output V_{out2} of the LP given by eq. (17) respectively.

6 Realization and simulation

To evaluate the performance of above structures, the real circuit was designed with two OPA660, realizing the structure of Fig. 5. There the adder was replaced by simpler resistive summing voltage divider. The transconductance (g_T) of the diamond transistors was adjusted on the basic value g_T = 1,9 mS, with external DC current source I_Q = - 0,1 mA. As mentioned before the change of this current gives the possibility of tuning or optimising the parameters of this filter.

The proposed circuit was simulated with PSpice using professional macro model of the OPA660. Resulting magnitude responses have confirmed the symbolical analysis and theoretical assumptions.

7 Conclusion

The given structures of the biquadratic ARC filter using the transconductance amplifiers and the voltage buffers are evidently right choice for high frequency applications. The simulated results have confirmed this conclusion. These filters can be practically implemented by the commercially available diamond transistors.

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References:

[1] BURR-BROWN, OPA660 - Wide bandwidth operational transconductance amplifier and buffer, *Reference manual*, PDS-1072E, Tucson, 1995.

[2] LEHMAN, K., Diamond transistor OPA660, *BB. Application Bulletin.* AB-181, Tucson, 1993.

[3] HENN, CH.-LEHMAN, K., Designing active filters with the diamond transistor PA660, *BB Application Bulletin*,. AB-190, Tucson, 1994.

[4] NATIONAL SEMICONDUCTOR, LM13700 - Dual operational transconductance amplifiers with linearizing diodes and buffers, *Reference manual*. 1994.

[5] TOUMAZOU, C., LIDGEY, F. J., HAIGH, D. G., *Analogue IC design: The current-mode approach*, Peter Peregrinus Ltd., London, 1990.

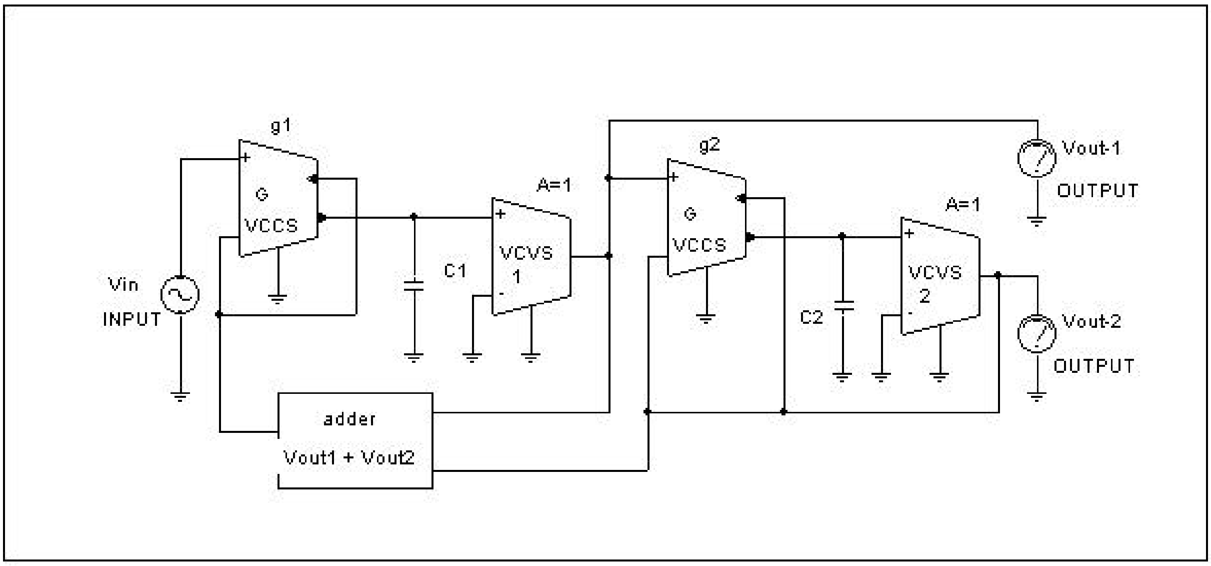

Fig. 5. ARC biquad with two loop feedback