

Electronically tunable multiple-mode biquadratic circuit employing OTAs and grounded capacitors

Hiroki Kawakami¹, Takao Tsukutani¹, Noboru Yabuki² and Yasuaki Sumi³

¹ Department of Electrical Engineering, Matsue College of Technology
14-4 Nishi-ikuma, Matsue 690-8518, Japan

² Department of Electronics and Computer Engineering, Tsuyama National College of Technology
624-1 Numa, Tsuyama 708-8509, Japan

³ Department of Information Systems, Tottori University of Environmental Studies
1-1 Wakabadai-kita, Tottori 689-1111, Japan

E-mail: ¹ tsukutani@matsue-ct.ac.jp, ² yabuki@tsuyama-ct.ac.jp, ³ sumi@kankyo-u.ac.jp

Abstract: This paper introduces an electronically tunable multiple-mode biquadratic circuit employing operational transconductance amplifiers (OTAs) and grounded capacitors. The basic circuit configuration is obtained from a second-order integrator loop structure consisting of lossless and lossy integrators. The multiple-mode biquadratic circuit can realize low-pass, band-pass, high-pass, band-stop and all-pass transfer functions by suitably choosing the current output terminals. Additionally, the circuit parameters ω_0 , Q and H can be set orthogonally through adjusting the bias currents of the OTAs. The biquadratic circuits enjoy very low sensitivities with respect to the circuit components.

Some examples are given together with simulated results by PSPICE.

1. Introduction

High performance active circuits have received much attention. The voltage- and current-mode circuits using active devices such as OTAs and second generation current conveyors (CCII) have been reported in the literature [1]-[7].

It is known that the OTA provides highly linear electronic tunability and wide tunable range of its transconductance gain. Also, the OTA-based circuit requires no external resistors, hence it is very suitable for integration. A biquadratic circuit is a very useful second-order function block for realizing high-order circuit transfer functions. The voltage- and current-mode biquadratic circuits only using the OTAs have been discussed previously [1],[4]-[7]. However, biquadratic circuit with multiple-mode operation (i.e. voltage-mode, current-mode, trans-admittance-mode and trans-impedance-mode operation) employing the OTAs have not yet been studied sufficiently.

This paper introduces an electronically tunable multiple-mode biquadratic circuit using the OTAs and two grounded capacitors. The circuit configuration is obtained from a second-order integrator loop structure consisting of the lossless and lossy integrators. The circuit can realize the low-pass, band-pass, high-pass, band-stop and all-pass transfer functions by choosing the appropriate current output terminals. Additionally, the circuit parameters ω_0 , Q and H can be tuned orthogonally by adjusting the bias

currents of the OTAs. It is clear from sensitivity analysis that the biquadratic circuits have very low sensitivities with respect to the circuit components. Some examples are given together with simulated results by PSPICE.

The biquadratic circuit configuration is very suitable for implementation in both bipolar and CMOS technologies.

2. OTA

Figure 1 shows the symbol for the OTA. This shows dual current output OTA (DO-OTA). The OTA with MOS transistors is shown in Fig.2.

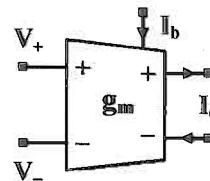


Figure 1. Symbol for OTA.

The output current I_o is given by

$$I_o = \pm g_m (V_+ - V_-) \quad (1)$$

where g_m denotes the transconductance gain.

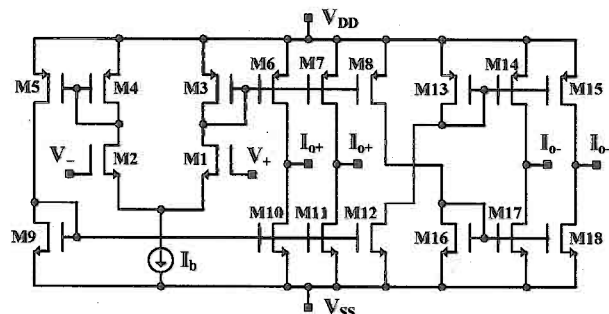


Figure 2. OTA with MOS transistors.

The transconductance gain can be characterized by

$$g_m = \left(\mu_n C_{ox} \frac{W}{L} I_b \right)^{\frac{1}{2}} \quad (2)$$

where μ_n , C_{ox} , W/L and I_b are the electron mobility of NMOS, gate oxide capacitance per unit area, transistor aspect ratio and bias current of the OTA, respectively. It is found that the resistance g_m is adjustable by a supplied bias current I_b .

3. OTA-C integrator loop structure

Figure 3 shows OTA and capacitor (OTA-C) integrator loop structure consisting of the loss-less and lossy integrators. The circuit is constructed with three DO-OTAs and two grounded capacitors.

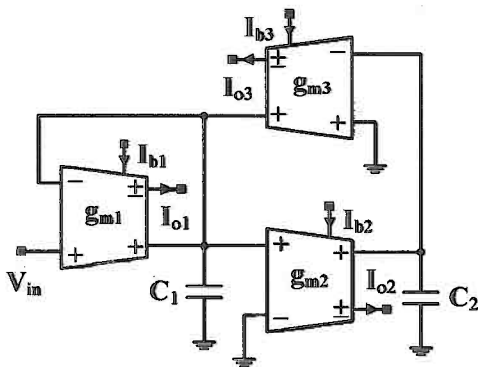


Figure 3. OTA-C integrator loop structure.

Routine analysis yields the current outputs $I_{o1}(s)$, $I_{o2}(s)$ and $I_{o3}(s)$ given by

$$I_{o1}(s) = \pm \frac{g_{m1}(s^2 C_1 C_2 + g_{m2} g_{m3}) V_{in}(s)}{s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (3)$$

$$I_{o2}(s) = \pm \frac{s C_2 g_{m1} g_{m2} V_{in}(s)}{s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (4)$$

$$I_{o3}(s) = \mp \frac{g_{m1} g_{m2} g_{m3} V_{in}(s)}{s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (5)$$

It is found from equations above that the current outputs $I_{o1}(s)$, $I_{o2}(s)$ and $I_{o3}(s)$ have the band-stop (BS), band-pass (BP) and low-pass (LP) characteristics in the trans-admittance-mode operation.

The band-pass (BP) and all-pass (AP) transfer functions can be realized by $I_{HP}(s) = I_{o1}(s) + I_{o3}(s)$ and $I_{AP}(s) = I_{o1}(s) - I_{o2}(s)$.

$$I_{HP}(s) = \pm \frac{g_{m1} s^2 C_1 C_2 V_{in}(s)}{s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (6)$$

$$I_{AP}(s) = \pm \frac{g_{m1}(s^2 C_1 C_2 - s C_2 g_{m2} + g_{m2} g_{m3}) V_{in}(s)}{s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (7)$$

In the band-pass and all-pass transfer functions, the condition below is needed.

$$g_{m2} = g_{m1} \quad (8)$$

The circuit parameters ω_0 , Q and H can be expressed as:

$$\omega_0 = \sqrt{\frac{g_{m2} g_{m3}}{C_1 C_2}}, \quad Q = \frac{1}{g_{m1}} \sqrt{\frac{C_1 g_{m2} g_{m3}}{C_2}}, \quad H = g_{m1} \quad (9)$$

4. Current- and voltage-mode biquadratic circuits

The current-mode biquadratic circuit is composed of adding the current-to-voltage converter shown in Fig.4 at the input terminal of the integrator loop structure in Fig.3.

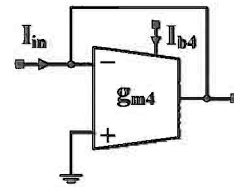


Figure 4. Current-to-voltage converter.

The circuit transfer functions at the current output terminals are given by

$$T_{BS}(s) = \frac{I_{o1}(s)}{I_{in}(s)} = \pm \frac{g_{m1} s^2 C_1 C_2 + g_{m2} g_{m3}}{g_{m4} s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (10)$$

$$T_{BP}(s) = \frac{I_{o2}(s)}{I_{in}(s)} = \pm \frac{g_{m1} s C_2 g_{m2}}{g_{m4} s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (11)$$

$$T_{LP}(s) = \frac{I_{o3}(s)}{I_{in}(s)} = \mp \frac{g_{m1} g_{m2} g_{m3}}{g_{m4} s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (12)$$

The circuit parameters ω_0 , Q and H become:

$$\omega_0 = \sqrt{\frac{g_{m2} g_{m3}}{C_1 C_2}}, \quad Q = \frac{1}{g_{m1}} \sqrt{\frac{C_1 g_{m2} g_{m3}}{C_2}}, \quad H = \frac{g_{m1}}{g_{m4}} \quad (13)$$

It is found from (13) that the circuit parameters can be tuned orthogonally by adjusting the bias currents of the OTAs.

The band-pass and all-pass transfer functions are realized by the currents $I_{HP}(s) = I_{o1}(s) + I_{o3}(s)$ and $I_{AP}(s) = I_{o1}(s) - I_{o2}(s)$.

$$T_{HP}(s) = \frac{I_{HP}(s)}{I_{in}(s)} = \pm \frac{g_{m1} s^2 C_1 C_2}{g_{m4} s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (14)$$

$$T_{AP}(s) = \frac{I_{AP}(s)}{I_{in}(s)} = \pm \frac{g_{m1} s^2 C_1 C_2 - s C_2 g_{m2} + g_{m2} g_{m3}}{g_{m4} s^2 C_1 C_2 + s C_2 g_{m1} + g_{m2} g_{m3}} \quad (15)$$

Thus, five current-mode transfer functions can be realized easily selecting the current output terminals. In addition, the biquadratic circuit has orthogonal tuning capability for the circuit parameters.

We consider below the effect of deviation of the circuit components on the biquadratic characteristic. Table 1 shows the sensitivities with respect to the circuit components (g_{m1} , g_{m2} , g_{m3} , g_{m4} , C_1 and C_2). The sensitivity takes the values of within 1.0. These values demonstrate that the biquadratic circuit enjoys very low sensitivities. It is also noted that the sensitivities do not depend upon the circuit component values.

Table 1. Sensitivity to circuit components.

x	$S_x^{o_0}$	S_x^Q	S_x^H
g_{m1}	0.0	-1.0	1.0
g_{m2}	0.5	0.5	0.0
g_{m3}	0.5	0.5	0.0
g_{m4}	0.0	0.0	-1.0
C_1	-0.5	0.5	0.0
C_2	-0.5	-0.5	0.0

The voltage-mode biquadratic circuit can be constructed with the integrator loop structure and the current-to-voltage converter in Fig.5. The circuit transfer functions, circuit parameters and sensitivities are same in the current-mode circuit.

In addition, the trans-impedance-mode biquadratic circuit is realized by adding the current-to-voltage converter of Fig.4 to the input terminal of the voltage-mode circuit.

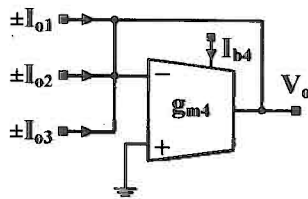


Figure 5. Current-to-voltage converter with current addition.

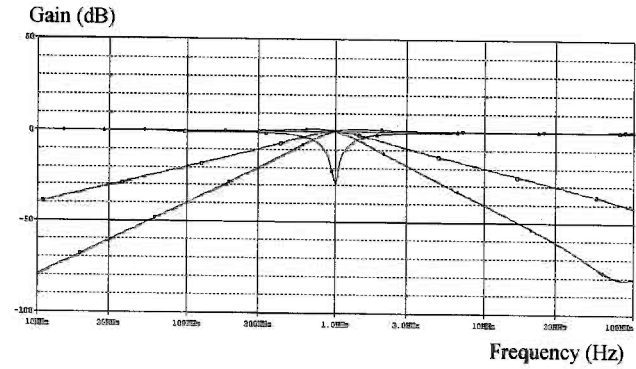
5. Design Example and Simulation Results

To verify the theoretical analysis, the voltage-mode biquadratic circuit was simulated using a PSPICE simulation program.

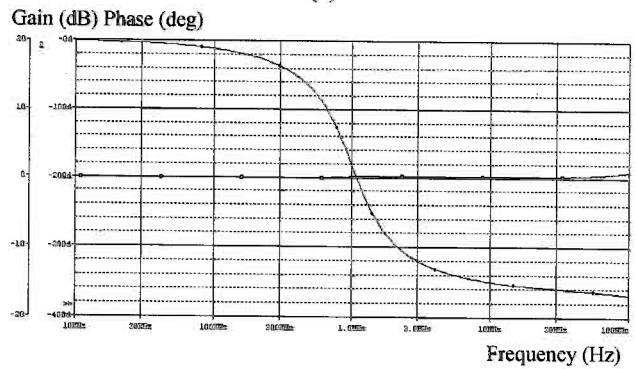
As an example, we consider a realization of the biquadratic characteristic with the cut-off frequency $f_0 (= \omega_0 / 2\pi) = 1\text{MHz}$, the quality factor $Q=1.0$ and the gain constant $H=1.0$. For PSPICE simulation, we have used the macro models of the OTA shown in Fig.2.

To realize the biquadratic characteristic above, we have determined that the bias currents and grounded capacitors were $I_{bi} (i=1,2,3,4) = 60\mu\text{A}$ and $C_1 = C_2 = 20\text{pF}$, respectively. Also, we have set the supply voltages and input voltage at $V_{DD} = -V_{SS} = 1.8\text{V}$ and $V_{in} = 0.5\text{V}$.

Figure 6 shows the frequency responses simulated with PSPICE. Figure 6 (a) shows the low-pass, band-pass, band-pass and band-stop responses. The all-pass response is shown in Fig.6 (b). They are favorable enough over a wide frequency range. The maximum power dissipation was about $109\mu\text{W}$. In this simulation, we have set the sizes of MOS transistors as $W=4\mu\text{m}$ and $L=2\mu\text{m}$.



(a)



(b)

Figure 6. Simulated responses.

Figure 7 shows the simulated band-pass responses with f_0 -tuning (i.e. $f_0=500\text{kHz}$, 1MHz and 2MHz), keeping $Q=2.0$ and $H=1.0$. In this case, the bias currents and grounded capacitors were $I_{bi} (i=1,2,3,4) = 3.75\mu\text{A}$, $15\mu\text{A}$, $60\mu\text{A}$ and $C_1=20\text{pF}$, $C_2=5\text{pF}$, respectively. The simulated band-pass responses with Q -tuning (i.e. $Q=0.707$, 1.0 and 2.0) are also shown in Fig.8, keeping $f_0=1\text{MHz}$ and $H=1.0$. In the responses, the bias currents were $I_{bi} (i=2,3,4) = 30\mu\text{A}$, $I_{b1} = 60\mu\text{A}$, $30\mu\text{A}$ and $7.5\mu\text{A}$, where $C_1=C_2=14.1\text{pF}$. It is made clear from the simulation responses that the circuit parameters ω_0 and Q can easily be tuned by adjusting the bias currents.

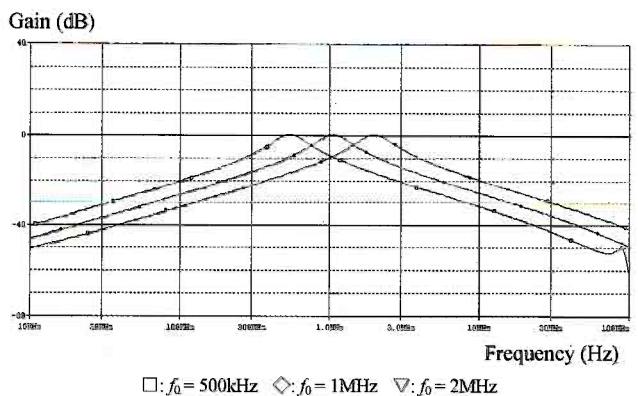


Figure 7. f_0 -tuning response.

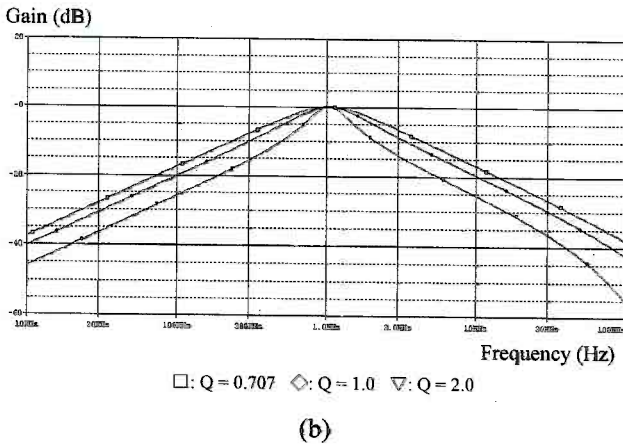


Figure 8. Q-turning response.

In this simulation, we have used the model parameters of 0.5 μ m MOS technology obtained through MOSIS listed in Table 2.

Table 2. Model parameters based on 0.5 μ m MOSIS.

NMOS	
LEVEL=3	PHI= 0.700000 TOX= 9.6000E-09
+ XJ= 0.200000U	TPG= 1 VTO= 0.6684
+ DELTA= 1.0700E+00	LD= 4.2030E-08
+ KP= 1.7748E-04	UO= 493.4 THETA= 1.8120E-01
+ RSH= 1.6680E+01	GAMMA= 0.5382
+ NSUB= 1.1290E+17	NFS= 7.1500E+11
+ VMAX= 2.7900E+05	ETA= 1.8690E-02
+ KAPPA= 1.6100E-01	CGDO= 4.0920E-10
+ CGSO= 4.0920E-10	CGBO= 3.7765E-10
+ CJ= 5.9000E-04	MJ= 0.76700 CJSW= 2.0000E-11
+ MJSW= 0.71000	PB= 0.990000
PMOS	
LEVEL=3	PHI= 0.700000 TOX= 9.6000E-09
+ XJ= 0.200000U	TPG= -1 VTO= -0.9352
+ DELTA= 1.2380E-02	LD= 5.2440E-08
+ KP= 4.4927E-05	UO= 124.9 THETA= 5.7490E-02
+ RSH= 1.1660E+00	GAMMA= 0.4551
+ NSUB= 8.0710E+16	NFS= 5.9080E+11
+ VMAX= 2.2960E+05	ETA= 2.1930E-02
+ KAPPA= 9.3660E+00	CGDO= 2.1260E-10
+ CGSO= 2.1260E-10	CGBO= 3.6890E-10
+ CJ= 9.3400E-04	MJ= 0.48300 CJSW= 2.5100E-10
+ MJSW= 0.21200	PB= 0.930000

6. Conclusions

An electronically tunable multiple-mode biquadratic circuit using OTAs and grounded capacitors has been proposed. We have demonstrated that the circuit can realize low-pass, band-pass, high-pass, band-stop and all-pass transfer functions by choosing the current output terminals, and that the circuit parameters ω_0 , Q and H can be tuned orthogonally by the bias currents of the OTAs. It has also been clear from sensitivity analysis that the biquadratic circuits have very low sensitivities to the circuit components. The simulated responses have been quite good over a wide frequency range.

The non-idealities of the OTA may affect the biquadratic characteristic. A solution on this must be discussed further.

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