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A multiple-mode universal biquadratic circuit employing OTAs and CF

Takao Tsukutani

Professor Emeritus, National Institute of Technology, Matsue College, Japan

Abstract: *This paper introduces a multiple-mode universal biquadratic circuit employing operational transconductance amplifiers (OTAs), current follower (CF) and grounded capacitors. The circuit can realize low-pass, band-pass, high-pass, band-stop and all-pass responses by choosing input terminals without any component matching conditions. Additionally, the circuit parameters ω_0, Q and H can be set orthogonally or independently by the bias currents of the OTAs and capacitors. The biquadratic circuit enjoys very low sensitivities to circuit active and passive components. The achievement examples are given together with simulation results by PSPICE.*

Keywords: *Multiple-mode circuit, Biquadratic characteristics, OTA, CF, CMOS technology*

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I.Introduction

High performance active circuits have received much attention. The voltage-mode and current-mode circuits using active devices such as OTAs, second generation current conveyors (CCIIs) etc. have been reported in the literature [1]-[6]. It is well known that the OTA provides highly linear electronic tunability and wide tunable range of its transconductance gain. Additionally, 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-mode and current-mode biquadratic circuits employing the OTAs have been discussed previously [1],[3]-[5]. In the biquadratic circuit design, it is much desirable that the circuit characteristics can be realized with no component matching conditions. Additionally, it is required to set the circuit parameters ω_0, Q and H orthogonally or independently.

In applications of analogue signal processing, it may be desirable to synthesize the biquadratic circuits (i.e. multiple-mode circuits) with input current or voltage and output current or voltage. However, the multiple-mode biquadratic circuits (i.e. current-mode, voltage-mode, trans-admittance-mode and trans-impedance-mode circuits) with above-mentioned performances have not yet been studied sufficiently.

This paper introduces the multiple-mode universal biquadratic circuit using the OTAs and CF. The basic current-mode circuit is obtained from two OTAs, one CF and two grounded capacitors. The multiple-mode biquadratic circuit is constructed with additional OTAs to the basic current-mode one. The circuit can realize the low-pass, band-pass, high-pass, band-stop and all-pass responses by choosing the appropriate input terminals without any component matching conditions. Additionally, the circuit parameters ω_0, Q and H can be tuned orthogonally or independently through adjusting the bias currents of the OTAs and capacitors. It is made clear from sensitivity analysis that the biquadratic circuit has very low sensitivities with respect to the circuit active and passive components.

Some examples are given together with simulated results by PSPICE. The workability was confirmed.

II.OTA and CF

Figure 1 shows the symbol for the OTA. This shows dual current output OTA.

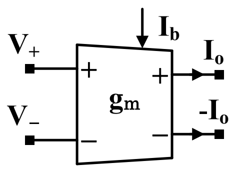


Figure 1: Symbol for OTA

The current output I_o is given by:

$$I_o = \pm g_m (V_+ - V_-) \tag{1}$$

where g_m denotes the transconductance gain.
In (1), the sign "±" shows the polarity of the current output.

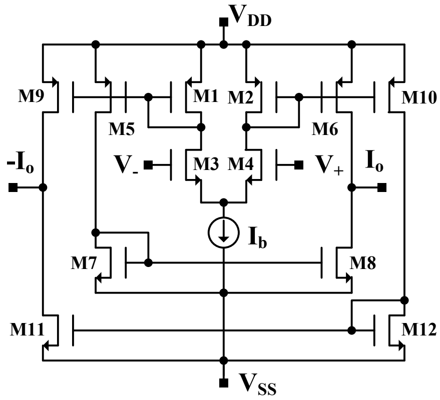


Figure 2: OTA with MOS transistors

The OTA with MOS transistors [5] is shown in Fig.2. The transconductance gain g_m can be characterized by:

$$g_m = \sqrt{\mu_n C_{ox} \frac{W}{L} I_b} \tag{2}$$

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, respectively. It is found that the transconductance gain is adjustable by a supplied bias current I_b.
Figure 3 shows the symbol for the CF. The current output I_o is given by:

$$I_z = \pm I_x \tag{3}$$

The CF with MOS transistors is shown in Fig.4. In general, the CF is realized by grounding the y-terminal of the CCII.

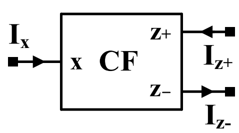


Figure 3: Symbol for CF

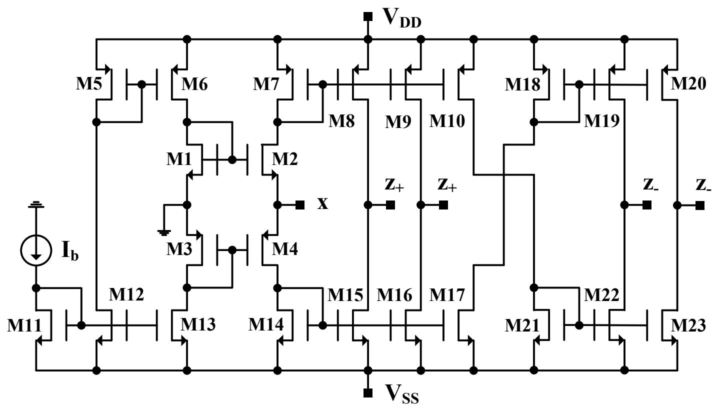


Figure 4: CF with MOS transistors

III. Circuit configurations and analysis

Figure 5 shows basic current-mode circuit configuration. The circuit is constructed with two OTAs, one CF and two grounded capacitors.

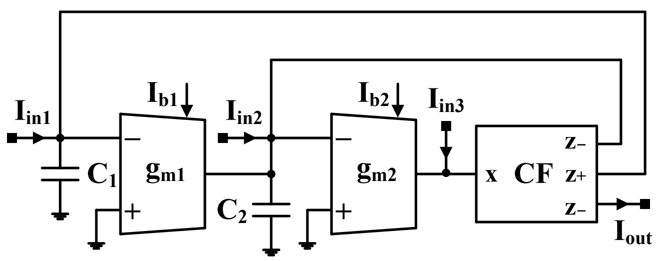


Figure 5: Basic current-mode circuit configuration

Routine analysis yields the current output $I_{out}(s)$ given by

$$I_{out}(s) = \frac{g_{m1}g_{m2}I_{in1}(s) - sC_1g_{m2}I_{in2}(s) + s^2C_1C_2I_{in3}(s)}{s^2C_1C_2 + sC_1g_{m2} + g_{m1}g_{m2}}$$

(4)

This circuit can realize various circuit transfer functions suitably choosing the input terminals. The low-pass transfer function $T_{LP}(s)$ ($=I_{out}(s)/I_{in}(s)$) can be realize by $I_{in1}(s)=I_{in}(s)$ and $I_{in2}(s)=I_{in3}(s)=0$. The band-pass and high-pass transfer functions $T_{BP}(s)$, $T_{HP}(s)$ are obtained from $I_{in2}(s)=I_{in}(s)$ and $I_{in3}(s)=I_{in}(s)$, respectively. The circuit transfer functions are given by:

$$T_{LP}(s) = \frac{g_{m1}g_{m2}}{s^2C_1C_2 + sC_1g_{m2} + g_{m1}g_{m2}}$$

(5)

$$T_{BP}(s) = -\frac{sC_1g_{m2}}{s^2C_1C_2 + sC_1g_{m2} + g_{m1}g_{m2}}$$

(6)

$$T_{HP}(s) = \frac{s^2C_1C_2}{s^2C_1C_2 + sC_1g_{m2} + g_{m1}g_{m2}}$$

(7)

The band-stop and all-pass transfer functions $T_{BS}(s)$, $T_{AP}(s)$ below can also be realized by $I_{in1}(s)=I_{in3}(s)=I_{in}(s)$ and $I_{in1}(s)=I_{in2}(s)=I_{in3}(s)=I_{in}(s)$.

$$T_{BS}(s) = \frac{s^2C_1C_2 + g_{m1}g_{m2}}{s^2C_1C_2 + sC_1g_{m2} + g_{m1}g_{m2}}$$

(8)

$$T_{AP}(s)=\frac{s^2C_1C_2-sC_1g_{m2}+g_{m1}g_{m2}}{s^2C_1C_2+sC_1g_{m2}+g_{m1}g_{m2}}$$

(9)

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

$$\omega_0=\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}},\quad Q=\sqrt{\frac{C_2g_{m1}}{C_1g_{m2}}},\quad H=1.0$$

(10)

Under the condition of $g_{m1}=g_{m2}=g_m$, the circuit parameters are modified to

$$\omega_0=\frac{g_m}{\sqrt{C_1C_2}},\quad Q=\sqrt{\frac{C_2}{C_1}},\quad H=1.0$$

(11)

It is found from equation above that the circuit parameters ω_0, and Q can be set orthogonally by adjusting the bias currents and capacitors.

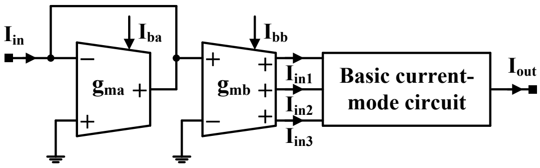


Figure 6: Current-mode biquadratic circuit

Figure 6 shows general current-mode circuit configuration. The circuit parameters ω_0, Q and H are given by:

$$\omega_0=\frac{g_m}{\sqrt{C_1C_2}},\quad Q=\sqrt{\frac{C_2}{C_1}},\quad H=\frac{g_{mb}}{g_{ma}}$$

(12)

The circuit parameter H can set independently by the bias currents without disturbing the circuit parameters ω_0 and Q.

Table 1: Sensitivity to circuit components (current-mode circuit).

x	ω_0	Q	H
g_{m1}	0.5	0.5	0.0
g_{m2}	0.5	-0.5	0.0
g_{ma}	0.0	0.0	-1.0
g_{mb}	0.0	0.0	1.0
C_1	-0.5	-0.5	0.0
C_2	-0.5	0.5	0.0

Table 1 shows the sensitivities with respect to the circuit components (g_{m1}, g_{m2}, g_{ma}, g_{mb} and C_1, C_2). We can find from these values that the circuits enjoy very low sensitivities to the circuit active and passive components. Additionally, it is noted that the sensitivities do not depend upon the circuit component values.

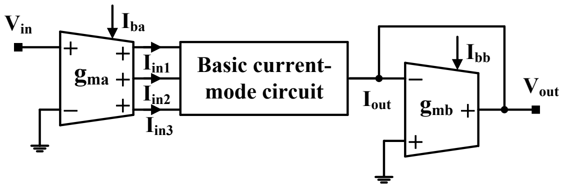


Figure 7: Voltage-mode biquadratic circuit

Figure 7 shows voltage-mode circuit configuration. In the circuit, the current output $I_{out}(s)$ is converted to the output voltage $V_{out}(s)$. The circuit parameters ω_0, Q and H are given by:

$$\omega_0 = \frac{g_m}{\sqrt{C_1 C_2}}, \quad Q = \sqrt{\frac{C_2}{C_1}}, \quad H = \frac{g_{ma}}{g_{mb}} \qquad (13)$$

The sensitivities to the circuit components are shown in Table 2. The sensitivities are about same for the current-mode ones.

Table 2: Sensitivity to circuit components (voltage-mode circuit).

x	ω_0	Q	H
g_{m1}	0.5	0.5	0.0
g_{m2}	0.5	-0.5	0.0
g_{ma}	0.0	0.0	1.0
g_{mb}	0.0	0.0	-1.0
C_1	-0.5	-0.5	0.0
C_2	-0.5	0.5	0.0

In addition, trans-admittance-mode and trans-impedance-mode circuits can easily be obtained by using the basic current-mode circuit in the same way. Their-mode circuits are shown in Figs 8 and 9.

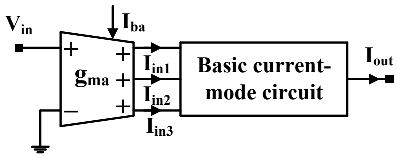


Figure 8: Trans-admittance-mode biquadratic circuit

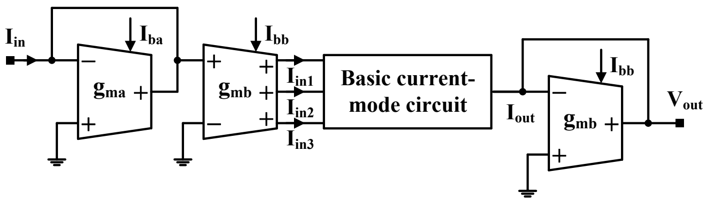


Figure 9: Trans-impedance-mode biquadratic circuit

IV. Design example and simulation results

To verify the theoretical analysis, the current-mode and voltage-mode biquadratic circuits were simulated using a PSPICE simulation program. At first, we consider the current-mode circuit characteristic with the cut-off frequency f_0 (=$\omega_0/2\pi$)=500kHz, quality factor Q=1.0 and gain constant H=1.0 as an example. In this simulation, we have used the macro models of the OTA and CF shown in Figs 2 and 4.

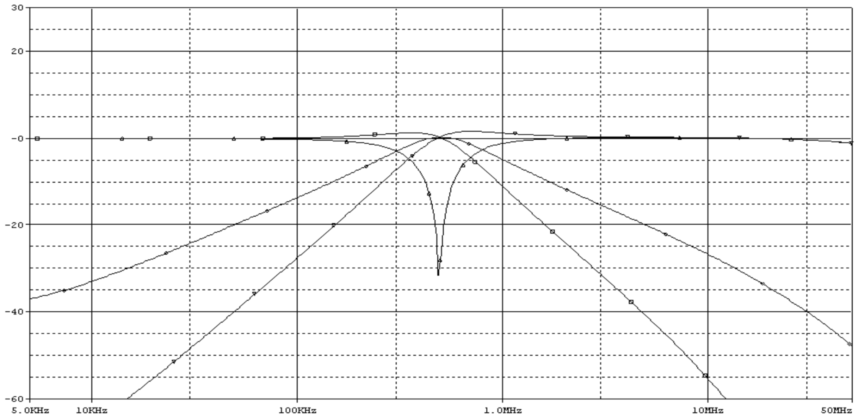
The circuit elements to realize the circuit characteristic above are indicated in Table 3. Also, we have set the bias current of the CF, the supply voltages and input current at I_b=20µA, V_{DD} = -V_{SS} =1.85V and I_{in} =10µA, respectively.

Table 3: Values of circuit elements

Element	Current-mode circuit	Voltage-mode circuit
I_{b1} (µA)	6.7	22.1
I_{b2} (µA)	6.7	22.1
I_{ba} (µA)	20	20
I_{bb} (µA)	20	20
C_1 (pF)	5	5
C_2 (pF)	5	5

Figure 10 shows the circuit responses simulated with PSPICE. Figure 8 (a) shows the low-pass, band-pass, band-pass and band-stop responses. The all-pass response is shown in Fig.8 (b). They are favorable enough over a wide frequency range. The power dissipation of this circuit was 0.760mW.

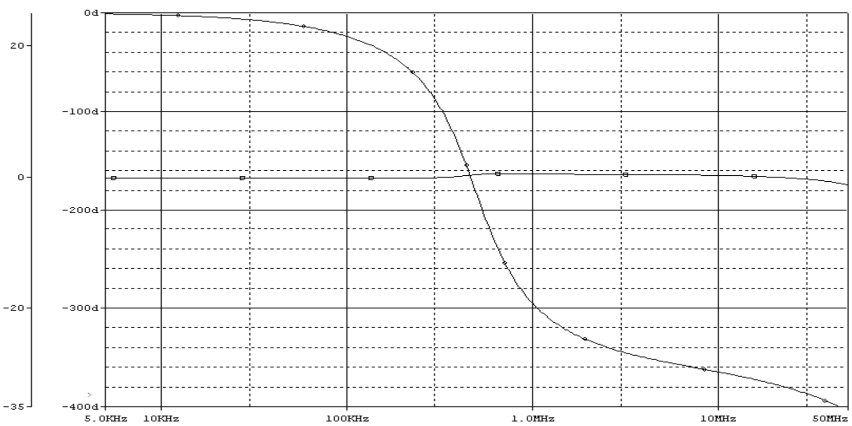
Gain (dB)



□: LP ◇: BP ▽: HP △: BS Frequency (Hz)

(a)

Gain (dB), Phase (deg)



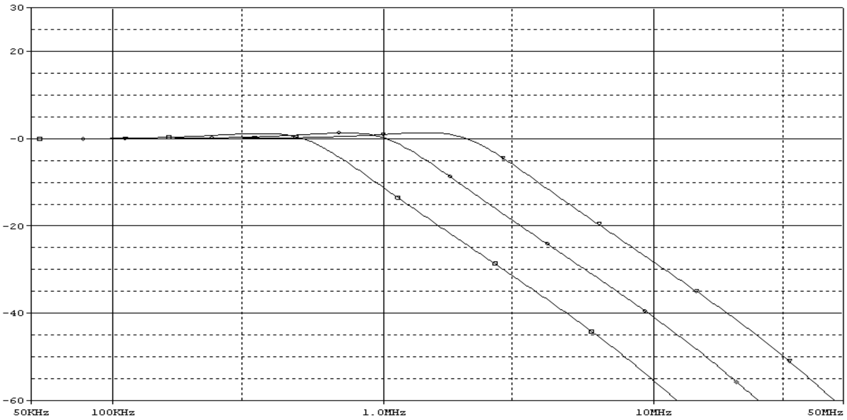
□: ｜$T_{AP}(j\omega)$｜ ◇: ∠$T_{AP}(j\omega)$ Frequency (Hz)

(b)

Figure 10: Simulation responses (current-mode circuit)

Figure 11 shows the simulated low-pass responses with f_0-tuning (i.e. f_0=500kHz, 1MHz and 2MHz) as Q=1.0 and H=1.0. Here, we set as I_{b1}=I_{b2}=6.7µA, 22.1µA and 80µA, respectively. It is made clear from the simulation responses that the circuit parameter f_0 can easily be tuned by adjusting the bias currents.

Gain (dB)

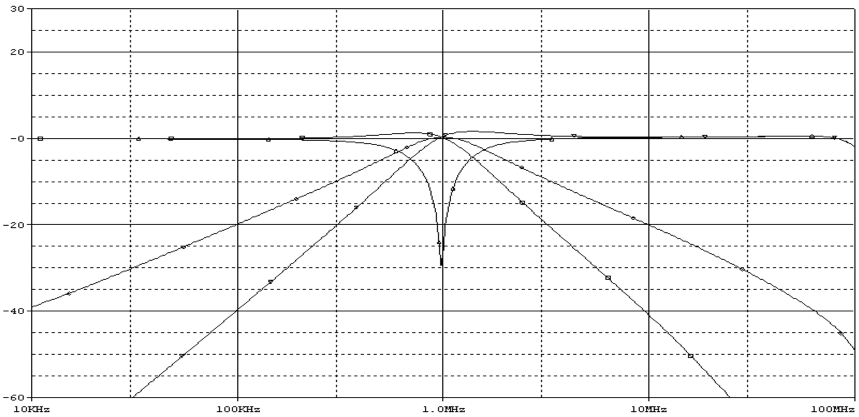


□: f_0 = 500kHz ◇: f_0 = 1MHz ◇: f_0 = 2MHz Frequency (Hz)

Figure 11: f_0-tuning responses (current-mode circuit)

Next, we consider the voltage-mode characteristic with f_0=1MHz, Q=1.0 and H=1.0. The bias currents and capacitors are shown in Table 3. Where the input voltage V_{in}=100mV. Figure 12 shows the simulated responses. In the circuit, the power dissipation was 1.24mW. The f_0-tuning responses in band-pass characteristic are shown in Fig.13. Where we varied as f_0=500kHz, 1MHz and 2MHz, keeping Q=1.0 and H=1.0. The bias currents were set as same values for the current-mode circuit. Good responses are obtained like as the current-mode ones.

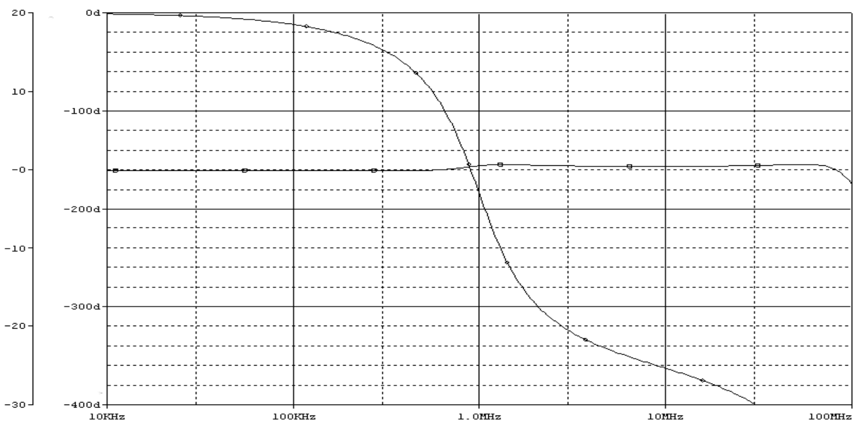
Gain (dB)



□: LP ◇: BP ▽: HP △: BS Frequency (Hz)

(a)

Gain (dB), Phase (deg)

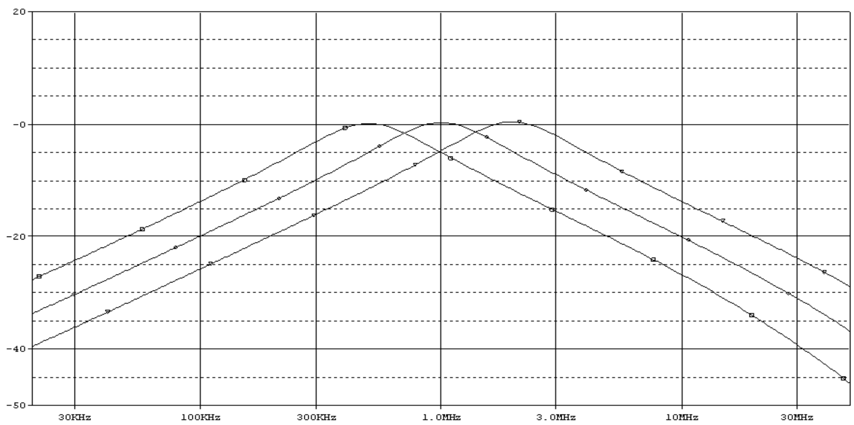


□: ｜$T_{AP}(j\omega)$｜ ◇: $\angle T_{AP}(j\omega)$ Frequency (Hz)

(b)

Figure 12: Simulation responses (voltage-mode circuit)

Gain (dB)



□: f_0 = 500kHz ◇: f_0 = 1MHz ◇: f_0 = 2MHz Frequency (Hz)

Figure 13: f_0-tuning responses (voltage-mode circuit)

In this simulation, the size of MOS transistors of the OTA in M1 to M4 have W/L=3μm/1.5μm, and other transistors have W/L=4μm/2μm. In the CF, we have set the size as W/L=4μm/2μm. Additionally, we have used the model parameters of 0.5μm MOS technology obtained through MOSIS.

V. Conclusions

A multiple-mode universal biquadratic circuit using OTAs, and CF 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 input terminals with no component matching conditions, and that the circuit parameters ω_0, Q and H can be tuned orthogonally or independently by the bias currents of the OTAs and capacitors. The simulated responses have been quite good over a wide frequency range. The circuit configuration is very suitable for implementation in CMOS technology.

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

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