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Second-Order Transconductance-Mode Universal Filter Based on CCCII and OTA

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Abstract: This research, based on Mason's formula, proposes a novel design for a second-order transconductance-mode universal filter with the operational transconductance amplifier (OTA) as the core and the second-generation current-controlled conveyor (CCCI) as the auxiliary. The circuit incorporates two OTAs, one CCCII, two grounded capacitors, and one grounded resistor. The quality factor Q and natural frequency f_o of the filter can be electronically tuned and are not sensitive to temperature. The input and output terminals of the circuit exhibit no loading effect, and the sensitivity of the circuit is low. At last, alternating frequency analysis, parameter scanning analysis, and temperature scanning analysis have been carried out by using Multisim software, confirming the correctness and effectiveness of the designed circuit.

Key words: second-order universal filter; transconductance-mode circuit; second-generation current-controlled conveyor (CCCI); operational transconductance amplifier (OTA)

CLC number: TN712

0 Introduction

The operational transconductance amplifier (OTA) is widely used in analog signal processing, measuring instruments, and communication systems. This is not only because its parameters can be electronically adjusted but also because its linearity is higher than that of a traditional operational amplifier, and its wide operating frequency range makes it more suitable for radio frequency and high frequency signal processing and transmission. Furthermore, various analog filters, sinusoidal oscillators, and general impedance converters based on OTAs have been developed^[1-3], and new active devices based on OTAs and their applications remain a focus of current research^[4-6]. However, the OTA-based voltage-mode inte-

grator does not output low impedance, resulting in failing to directly form a voltage negative feedback circuit. Similarly, in an OTA-based current-mode integrator, the input is not of low impedance, preventing it from directly forming a current negative feedback circuit. Thus, the output of the OTA-based voltage/transconductance-mode filter often needs to add another voltage buffer and a single OTA cannot function as a voltage buffer. Likewise, the inputs of the OTA-based current/transconductance-mode filter often require an additional current buffer and a single OTA cannot function as a current buffer. To this end, solving these problems often leads to complex circuit structures.

The second-generation current-controlled conveyor (CCCI) is a current-mode device. Its parameters can not

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only be electronically adjusted, but also, its two inputs function as a voltage buffer. Relative to the OTA, it can accept either a voltage or a current input, which significantly broadens its application in analog circuits^[7-9]. However, the resistance at the x terminal of the CCCII is controlled by the bias current. When adjusting the circuit parameters, the change in the resistance may lead to circuit instability. By contrast, the input impedance of the OTA is infinite, so these two characteristics, for OTA and CCCII, are complementary.

In order to get a better analog filter, we use the OTA as the core and the CCCII as an auxiliary component, making full use of their respective advantages. Based on Mason's formula, a second-order transconductance-mode universal filter is designed by virtue of two OTAs, one CCCII, two grounded capacitors, and one grounded resistor. Computer simulations demonstrate that the designed circuit is both correct and effective.

1 Circuit Design

1.1 Design Basis

In the development history of filters, second-order filters occupy a very important position because they come in various types, show a simple structure, feature a mature design, and serve as the basis of higher-order filters. Within the second-order filter family, the double-integrator loop filter is particularly favored by designers, and it is often referenced in the design of modern current-mode circuits^[10-12]. There are several methods to design double-integrator loop filters, such as multi-loop feedback method, block graph method, node admittance matrix expansion method, Mason's formula method, etc.^[13-15]. Among them, the Mason's formula method is more commonly used because it offers a straightforward method to address the transfer function of a double-integrator loop filter. The original Mason's formula is as follows

$$H = \frac{\sum_i P_i \Delta_i}{\Delta}, \quad (1)$$

where

$$\Delta = 1 - \sum_j L_j + \sum_{m,n} L_m L_n - \sum_{p,q,r} L_p L_q L_r + \dots \quad (2)$$

H is the transmission function, Δ is the characteristic determinant of the signal flow graph, Δ_i is the cofactor of the characteristic determinant of the i -th forward channel. Specifically, Δ_i is the characteristic determinant of the remaining subgraph, excluding the loop that inter-

acts with the i -th forward channel. Additionally, P_i denotes the i -th forward channel gain from input to output. In (2), L_j is the gain of the j -th loop. The second term is the sum of the gains of all individual loops, the third term is the sum of the products of the gains of all pairs of non-touching loops, and the fourth term is the sum of the products of the gains of all three non-touching loops.

There are only two loops, one large loop and one small loop, in the double-integrator loop filter, and they are in contact, so only the first two terms are left in (2). For simplicity, only one forward channel is selected at a time, and it is always in contact with the two loops, then $\Delta_i = 1$ in (1), so (1) becomes

$$H = \frac{P_i}{1 - \sum_j L_j}. \quad (3)$$

From this, it can be seen that designing a double-integrator loop filter means designing the numerator and denominator in equation (3).

1.2 Filter Design

According to the structure of a traditional double-integrator loop filter, the loop of the designed filter can be constructed, as shown in Fig. 1.

Based on Fig. 1 and the OTA integrator and CCCII buffer circuit, the corresponding circuit is constructed, as shown in Fig. 2. It consists of a noninverting voltage-

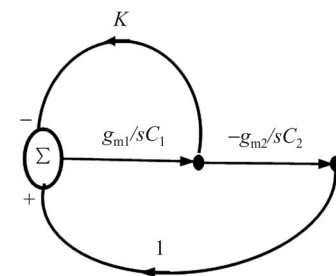


Fig.1 Signal flow diagram of double-integrator filter loop

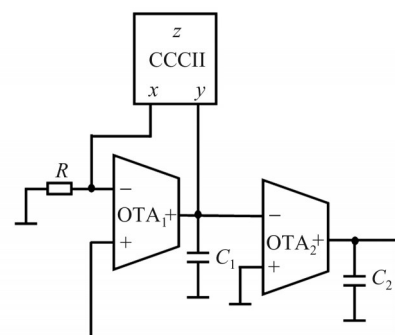


Fig.2 The filter loop

mode integrator using one OTA, an inverting voltage-mode integrator using one OTA, and a buffer consisting of one CCCII and one resistor.

Assuming the small loop is broken, the gain of the large loop is $-g_{m1}g_{m2}/s^2C_1C_2$. If the large loop is broken, the gain of the small loop is $-g_{m1}R/sC_1(R_x+R)$. Therefore, the sum of the loop gains is

$$\sum_j L_j = -g_{m1}g_{m2}/s^2C_1C_2 - g_{m1}R/sC_1(R_x+R). \quad (4)$$

The introduction of coefficient $K=R/(R_x+R)$ in the small loop can be used to adjust the Q factor of the filter. Simultaneously, it introduces local voltage-series negative feedback, which can stabilize the quiescent operating point.

It has been found that the OTA and CCCII have no input terminals with zero impedance, so the current source should not be used as input. However, the OTA and CCCII have input terminals with infinite impedance, so voltage sources are suitable for input. Since the outputs of the OTA and CCCII are currents, to obtain current outputs, the OTA is extended to a dual-output OTA (DOOTA), and the CCC II is implemented using a positive-output CCC II (CCC II+). By lifting the non-inverting input terminal of OTA₂ from ground and connecting the voltage source V_i with I_{o2} as the output, the forward path gain becomes $P_2=g_{m2}$. Substituting P_1 and (4) into (3) and simplifying, the transconductance-mode high-pass transfer function is obtained as

$$H_{HP} = \frac{I_{o2}}{V_i} = \frac{g_{m2}s^2}{s^2 + g_{m1}Rs/C_1(R_x+R) + g_{m1}g_{m2}/C_1C_2}. \quad (5)$$

If I_{o1} is selected as the output, the forward channel gain from V_i to I_{o1} is $P_1=g_{m1}g_{m2}/sC_2$, P_1 and (4) are substituted into (3), and the transconductance-mode band pass transmission function is arranged as

$$H_{BP} = \frac{I_{o1}}{V_i} = \frac{g_{m1}g_{m2}s/C_2}{s^2 + g_{m1}Rs/C_1(R_x+R) + g_{m1}g_{m2}/C_1C_2}. \quad (6)$$

If I_{o3} is selected as the output, then the forward channel gain from V_i to I_{o3} is $P_3=g_{m1}g_{m2}/s^2C_1C_2(R_x+R)$, P_3 and (4) are substituted into (3), and the transconductance-mode low-pass transmission function is arranged as

$$H_{LP} = \frac{I_{o3}}{V_i} = \frac{g_{m1}g_{m2}/C_1C_2(R_x+R)}{s^2 + g_{m1}Rs/C_1(R_x+R) + g_{m1}g_{m2}/C_1C_2}. \quad (7)$$

Equations (5)-(7) demonstrate that the circuit can simultaneously implement high-pass, band-pass, and low-pass filtering. This confirms that it functions as a second-order transconductance-mode universal filter with a single input and three outputs.

Figure 3 illustrates the designed second-order transconductance-mode universal filter circuit, in which the bias currents I_{B1} and I_{B2} are realized by a simple synchronous transconductance voltage control circuit, and I_{B3} is generated by a single OTA transconductance voltage control circuit^[16].

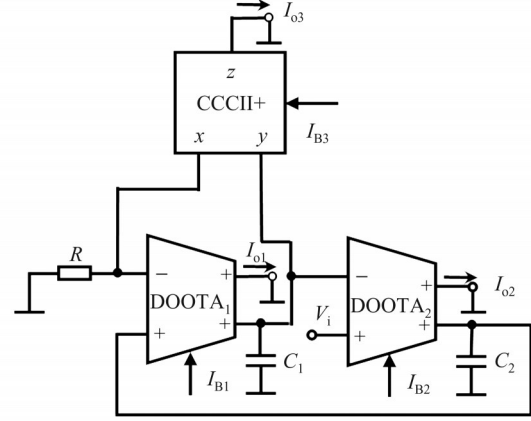


Fig. 3 Second-order transconductance-mode universal filter

2 Circuit Analysis

By comparing (5) - (7) with the standard second-order filter transmission function, the natural frequency f_o of the filter is

$$f_o = \frac{\sqrt{g_{m1}g_{m2}/C_1C_2}}{2\pi}. \quad (8)$$

For simplicity, $C_1=C_2=C$, $g_{m1}=g_{m2}=g_m=I_B/2V_T$ are usually selected, I_B is the bias current of the OTA, V_T is the thermal voltage. Substituting them into (8) yields

$$f_o = \frac{I_B}{4\pi V_T C}. \quad (9)$$

Considering the parasitic resistance $R_x=V_T/2I_{B3}$ of the CCC II, the quality factor Q of the filter obtained from (7) is

$$Q = \sqrt{\frac{g_{m2}C_1}{g_{m1}C_2}} \left(1 + \frac{R_x}{R}\right) = 1 + \frac{R_x}{R} = 1 + \frac{V_T}{2RI_{B3}}. \quad (10)$$

Therefore, adjusting the bias current of two OTAs allows for the linear tuning of the filter's natural frequency without affecting the quality factor. Similarly, by adjusting the bias current of the CCCII, the quality factor of the filter can be adjusted without affecting the natural frequency, so that the orthogonal adjustment of the two can be realized.

From (5) - (7), the high-pass, band-pass, and low-pass transconductance gains can also be obtained as follows

$$H_{HP0} = g_{m2} = \frac{I_B}{2V_T}, \quad (11)$$

$$H_{BP0} = \left(1 + \frac{R_x}{R}\right) \frac{C_1 g_{m2}}{C_2} = \left(1 + \frac{R_x}{R}\right) \frac{I_B}{2V_T} = Q \frac{I_B}{2V_T}, \quad (12)$$

$$H_{LP0} = \frac{1}{R_x + R} = \frac{1}{V_T/2I_{B3} + R}. \quad (13)$$

Therefore, adjusting the bias current I_B of two OTAs can linearly adjust the natural frequency of the filter without affecting the quality factor. However, it does affect the high-pass and band-pass gains. Similarly, the quality factor of the filter can be adjusted by modifying the bias current I_{B3} of the CCCII, which does not affect the natural frequency and high-pass gain but affects the band-pass and low-pass gain.

From (8)-(10), the sensitivity of natural frequency and quality factor can be calculated as

$$S_{f_o}^{f_o} = S_{f_o}^{f_o} = \frac{1}{2}, S_{C_1}^{f_o} = S_{C_2}^{f_o} = -\frac{1}{2}, \quad (14)$$

$$S_{f_o}^Q = -S_{f_o}^Q = \frac{1}{2}, S_{C_1}^Q = -S_{C_2}^Q = \frac{1}{2}, \quad (15)$$

$$S_{I_{B3}}^Q = \frac{R_x/R}{1 + R_x/R} - 1 = \frac{-1}{1 + V_T/2RI_{B3}}. \quad (16)$$

The above formulae show that the filter enjoys low passive and active sensitivity.

By observing (10), it can be seen that the quality factor is related to V_T , and $V_T = KT/q$, so Q is affected by temperature. To mitigate this effect, an analog resistor composed of the CCCII is used instead of R , and $R = V_T/2I_{B4}$ is substituted into (10), then the quality factor becomes

$$Q = 1 + \frac{R_x}{R} = 1 + \frac{I_{B4}}{I_{B3}}. \quad (17)$$

Thus, the influence of temperature on the quality factor is eliminated.

By observing (9), it can be seen that natural frequency is related to V_T , and $V_T = KT/q$, so (9) can be written as

$$f_o = \frac{I_B q}{4\pi KTC}, \quad (18)$$

where q is the electron charge, $q = 1.6 \times 10^{-19} \text{ C}$, K is the Boltzmann constant, $K = 1.38 \times 10^{-23} \text{ J/K}$, T is the absolute temperature, $T = 273 + t$, and t is the Celsius temperature. It can be observed that the natural frequency is dependent on temperature and can be stabilized by using simple techniques, such as in a constant single OTA transconductance voltaic circuit, since the bias current is satisfied^[16]

$$I_B = \frac{V_C - V_{EE} - 2U_{BE}}{R}, \quad (19)$$

where V_C is the external control voltage, V_{EE} is the negative power supply of the OTA, U_{BE} is the emitter junction voltage of the transistor in the OTA, and R is the thermistor with negative temperature coefficient. Then, f_o is the explicit function of T and I_B , while I_B is the explicit function of R . It can be deduced from (18)-(19) that there is

$$\frac{df_o}{dT} = -\frac{KI_B}{T} \times \frac{dR/R}{dT} - \frac{KI_B}{T^2}. \quad (20)$$

To stabilize f_o , (20) can be set to zero, and then the temperature coefficient α of the thermistor is

$$\alpha = \frac{dR/R}{dT} = -\frac{1}{T}. \quad (21)$$

If the circuit operates near the room temperature, the natural frequency of the filter can be stabilized by using a thermistor of $\alpha = 1/300 = -0.33\%/K$.

3 Computer Analysis

Firstly, the commercial OTA model LM136000 is selected as OTA1 and OTA2 in the NI MULTISIM 11.0 software simulator library. Secondly, the transistor PR200N and NR200N models are established, and then the CCCII circuit is built. Finally, the circuit in Fig. 3 is built with a power supply of $\pm 2.5 \text{ V}$. Setting $C_1 = C_2 = 1 \text{ nF}$, $R = 100 \Omega$, $I_{B3} = 130 \mu\text{A}$, $I_B = 326.56 \mu\text{A}$, the design values of the natural frequency and quality factor are obtained from (9)-(10): $f_o = 1 \text{ MHz}$, $Q = 2$. The design values of passband gain are determined from (11)-(13): $H_{HP0} = 6.28 \text{ mS}$, $H_{BP0} = 12.56 \text{ mS}$, $H_{LP0} = 5 \text{ mS}$.

Shown in Fig. 4 are the simulation results of frequency analysis, which indicates that the simulation value of f_o is 995 kHz, and the relative error is -0.50% . The simulation value of Q is 1.92, and the relative error is -4.00% . The simulation values of passband gain are $H_{HP0} = 6.23 \text{ mS}$, $H_{BP0} = 12.24 \text{ mS}$, $H_{LP0} = 5.0003 \text{ mS}$, and the relative errors are -8.00% , -2.55% , 0.05% , respectively.

To confirm that the natural frequency is linearly controlled by I_B , set $I_B = 32.656 \mu\text{A}$, $326.56 \mu\text{A}$, $3265.6 \mu\text{A}$ and the remaining parameters unchanged, from (9)-(10), we find the natural frequency $f_o = 0.1 \text{ MHz}$, 1 MHz , 10 MHz and $Q = 2$. The simulation results are shown in Fig. 5 (only low-pass filtering is given).

To confirm that the number of quality factors is controlled by I_{B3} , I_{B3} is set up to $130 \mu\text{A}$, $14.4 \mu\text{A}$, $6.84 \mu\text{A}$, and other parameters remain unchanged. Then, (9)-(10) show that $f_o = 1 \text{ MHz}$ and $Q = 2, 10, 20$, and the simu-

lation results are illustrated in Fig. 6 (only high-pass filtering is given).

To observe the influence of temperature on the natural frequency of the filter, temperature scanning analysis is carried out on the circuit in Fig. 3, and the bandpass simulation results are shown in Fig. 7. It can be observed that f_o increases from 1 MHz to 1.091 MHz when the temperature decreases from 27 °C to 0 °C. After applying thermistor compensation with a negative temperature coefficient, the bandpass simulation results are shown in Fig. 8, which demonstrates that the natural fre-

quency hardly changes with temperature.

It can be seen that the above simulation results are consistent with the theory.

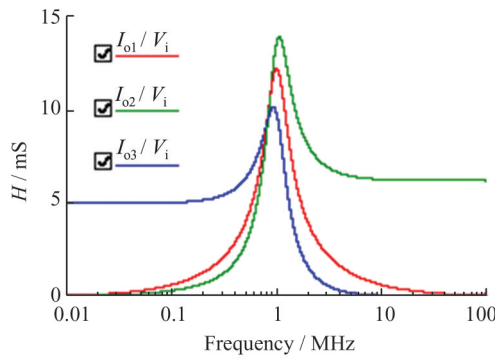


Fig. 4 AC frequency analysis of transconductance-mode circuit

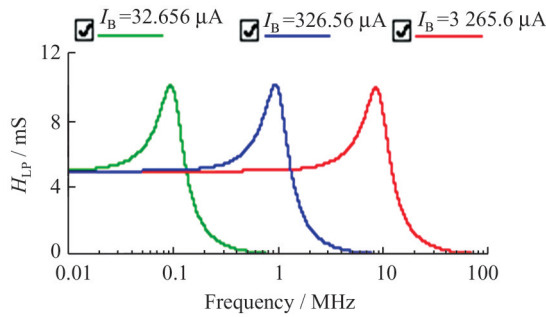


Fig. 5 Relationship between natural frequency and I_B

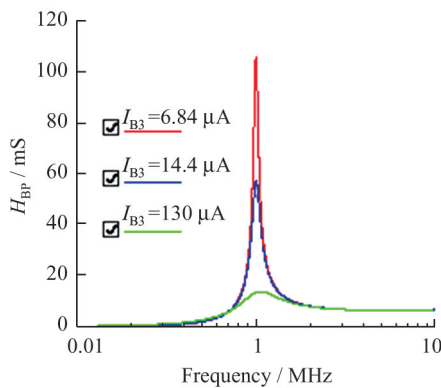


Fig. 6 Relationship between quality factor and I_{B3}

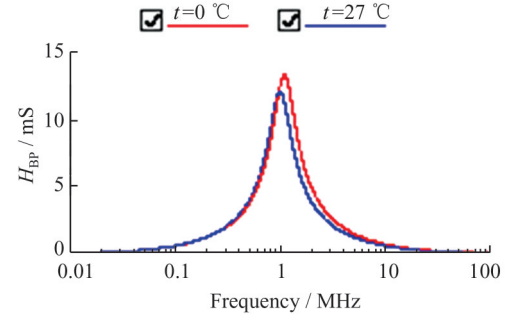


Fig. 7 Temperature scanning analysis of uncompensated bandpass filter

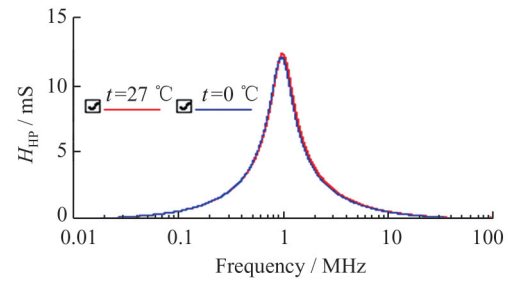


Fig. 8 Temperature scanning analysis of the compensated bandpass filter

4 Conclusion

According to Mason's formula, a second-order transconductance-mode universal filter is designed using the OTA and CCCII. The designed circuit has the following characteristics:

- 1) The natural frequency and the quality factor can be controlled orthogonally, and the natural frequency is proportional to bias current I_B of the OTA;
- 2) The natural frequency and the quality factor are insensitive to temperature;
- 3) Use of ground capacitance and ground resistance;
- 4) Q depends on the bias current I_{B3} of the CCCII, and it is easy to obtain a higher Q value;
- 5) High-input impedance and high-output impedance.
- 6) Low passive and active sensitivity.

In fact, the designed circuit also has disadvantages, for instance, the quality factor cannot be less than 1, and the temperature coefficient of the thermistor is dependent on temperature.

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基于OTA和CCCII二阶跨导模式通用滤波器

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摘要: 本文基于Mason公式, 提出了一种以OTA为核心, CCCII为辅助的二阶跨导模式通用滤波器的设计方案。该电路包括两个OTA、一个CCCII、两个接地电容器和一个接地电阻。该滤波器的品质因数 Q 和自然频率 f_0 可以电控调谐, 且对温度不敏感。该电路的输入端和输出端均无加载效应, 电路的灵敏度较低。最后利用Multisim软件进行了交流频率分析、参数扫描分析和温度扫描分析, 验证了所设计电路的正确性和有效性。

关键词: 二阶通用滤波器; 跨导模式电路; 第二代电流控制传输器; 运算跨导放大器

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