Operational transconductance amplifier based voltage-mode universal filter

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Received 10 October 2003; revised 21 March 2005; accepted 23 June 2005

An operational transconductance amplifier (OTA) based voltage-mode universal filter is presented. The proposed circuit employs four OTAs with two grounded capacitors and realizes lowpass, bandpass and highpass filter functions. The pole-frequency \( w_p \) and pole-Q, \( Q_p \), are orthogonally adjustable by proper choice of transconductance gains of OTAs and capacitor values. The proposed universal filter can also be used for the realization of notch filter function. In addition a current feedback amplifier (CFA)-based universal filter is also realized by converting the OTA-based circuit using standard transformation method\(^1\) [Hou C L & Wang W Y, IEE Proc Circuits Devices and Systems, 144, 209-212.]. Both the circuits have been studied in detail. The simulation results have also been included.

Keywords: Operational transconductance amplifier, Amplifier, Universal filter, OTAs, Current feedback amplifier, Transconductance

IPC Code: H03H

1 Introduction

An operational transconductance amplifier (OTA) is widely used as an active element in analog signal processing circuits. It is a differential input voltage controlled current source (DVVCS) device. The port relation of OTA as shown in Fig. 1 is

\[(V^+ - V^-)g_m = I_o \] … (1)

where, \( V^+ - V^- \) is the differential input voltage, \( I_o \) is the OTA output current and \( g_m \) is the transconductance gain of the operational transconductance amplifier determined by the relation

\[g_m = (I_B/2V_T),\]

where, \( I_B \) is the bias current of OTA and \( V_T \) is the voltage equivalent of temperature equal to 26 mV at room temperature.

OTA provides linear variation of transconductance gain \( g_m \) over a fairly wide range and due to the dependence of \( g_m \) on the bias current \( I_B \) of OTA, circuit parameters of interest such as pole frequency, quality factor \( Q \) in case of filters and frequency of oscillation in case of oscillators etc. can be electronically tuned. Also due to the presence of transconductance gain parameter \( g_m \), circuits realizing filters, oscillators and gyrators, etc. can be designed in such a way that they are free from passive resistors. Also due to current source at the output of OTA, the frequency response of OTA circuits is much better than op-amp-based circuits.

Owing to their attractive features discussed above, the transconductance amplifiers are widely used in the realization of filters, sinusoidal oscillators, grounded and floating inductors\(^2\-6\) and in non-linear circuit applications\(^7\). OTA-C circuits enjoy easy IC implementation specially when all capacitors are grounded.

Universal filters find wide applications in the field of communication and instrumentation engineering, their utility increases when they are capable of providing all the filter functions simultaneously for a single voltage or current source without changing the basic structure of the circuit. Many voltage-mode and
current-mode universal filters are reported in the literature.\textsuperscript{8-12}

The proposed circuit for the realization of universal filter employs only four OTAs and two grounded capacitors as against the circuit given elsewhere\textsuperscript{3} and provides lowpass, bandpass and highpass filter functions simultaneously for an analog input source. Notch filter can also be obtained by summing up lowpass and highpass responses which requires an additional OTA summer shown in Fig. 2. By appropriate choice of transconductance gains of various OTAs the pole-frequency $\omega_p$ and pole-$Q$, $Q_p$, can be orthogonally tuned. The electronic tuning of both the parameters is inherent to the circuit. The component spread is small. The sensitivity figures are fairly low.

In the end OTA-based universal filter has been converted into an equivalent current feedback amplifier (CFA)-based universal filter using available transformation techniques\textsuperscript{1}. The simulation results of both the filter circuits are included.

2 Circuit Description and Analysis

The circuit of OTA-based universal filter is depicted in Fig. 3. The simple circuit analysis using OTA port relation given in Eq. (1) yields the following voltage transfer ratio's of the universal filter.

\[
\frac{V_{LP}}{V_{in}} = \frac{g_m g_m g_m / C_1 C_2 g_m}{D(s)} \quad \text{…(2)}
\]

\[
\frac{V_{BP}}{V_{in}} = \frac{-(g_m / g_m) C_1 s}{D(s)} \quad \text{…(3)}
\]

\[
\frac{V_{HP}}{V_{in}} = \frac{(g_m / g_m) s^2}{D(s)} \quad \text{…(4)}
\]

\[
V_{Notch} = (V_{LP} + V_{HP}) V_{in} \quad \text{…(5)}
\]

where

\[
D(s) = s^2 + (g_m / C_1) s + g_m g_m g_m / C_1 C_2 g_m
\]
The pole-frequency, $\omega_p$ and pole-$Q$, $Q_p$ for the filter are given by

$$\omega_p = \frac{g_{m1}g_{m3}g_{m4}}{C_1C_2g_{m2}}$$ \hspace{1cm} \text{(6)}$$

$$Q_p = \frac{g_{m1}g_{m2}C_1}{g_{m2}g_{m3}C_2}$$ \hspace{1cm} \text{(7)}$$

Substituting,

$$g_{m1} = g_{m4} = g', g_{m2} = g_{m3} = g, \text{ and } C_1 = C_2 = C$$ \hspace{1cm} \text{(8)}$$

in Eqs (6) and (7), The expressions for $\omega_p$ and $Q_p$ modifies to,

$$\omega_p = \frac{g'}{C}$$ \hspace{1cm} \text{(9)}$$

$$Q_p = \frac{g'}{g_m}$$ \hspace{1cm} \text{(10)}$$

Equations (9) and (10) explain the operation of the circuit for the conditions depicted in Eq. (8). First the pole-frequency $\omega_p$ can be electronically tuned to the required value through $g'$ and then pole-$Q$, $Q_p$ can be adjusted through $g_m$. On the other hand at any point of time the quality factor of the filter can be varied electronically through $g_m$ without disturbing the setting of pole-frequency $\omega_p$. Moreover, if we vary the pole frequency $\omega_p$ through a gang capacitor (which is possible only in discrete circuit) then the tuning of $\omega_p$ and $Q_p$ becomes completely independent of each other.

Other suitable proposition is to always keep the ratio $g'/g_m$ a constant value such that whenever $g_m$ varies $g_m$ also varies to keep the ratio of $g'/g_m$ a constant that keeps $Q_p$ at a constant value. This proposition is good where we do not want to change the quality factor once it is fixed for some value also the temperature variation effects on the filter performance are reduced.

3 Simulation of OTA-Universal Filter Circuit

The proposed universal filter as shown in the Fig. 3. is simulated using LM13700 OTA model on PSpice based software for $f_p = 76.13$ KHz and $Q_p = 1$. The designed element values were, $C_1 = C_2 = 10nF$, and $I_{B1} = I_{B2} = I_{B3} = I_{B4} = 250 \mu A$. The frequency response plots were obtained for notch filter and for lowpass, bandpass and highpass filters as shown in Fig. 4 and Fig. 5, respectively. The simulated results are found to be close to those of theoretical values specially for pole frequency $f_p$, whereas pole $Q$ has slight deviation which can be afforded.

The OTA voltage-mode universal filter has been transformed into a current feedback amplifier (CFA) based circuit using the technique described.
elsewhere\textsuperscript{1}. The transformed CFA-based universal filter is shown in the Fig. 6 and its frequency response curves are given in Figs 7 and 8, respectively.

4 CFA-Based Active Universal Filter

The circuit obtained from proposed OTA-universal filter through transformation using transformation method\textsuperscript{1} is shown in Fig. 9. The voltage transfer functions of the CFA-universal filter were obtained using simple circuit analysis, and are given as follows

\[
V_{LP}(s) = \frac{G_1G_3G_4/C_1C_2G_2}{s^2+sG_3/C_1+G_1G_3G_4/C_1C_2G_2} \quad \text{...(11)}
\]

\[
V_{HP}(s) = \frac{s^2G_1/G_2}{s^2+sG_3/C_1+G_1G_3G_4/C_1C_2G_2} \quad \text{...(12)}
\]

\[
V_{BP}(s) = \frac{sG_1G_3/C_1G_2}{s^2+sG_3/C_1+G_1G_3G_4/C_1C_2G_2} \quad \text{...(13)}
\]

From the above equations the pole-frequency \( \omega_p \) and pole-\( Q \) are given by

\[
\omega_p = \sqrt{\frac{G_1G_3G_4}{C_1C_2G_2}} \quad \text{...(14)}
\]

\[
Q_p = \frac{G_1G_3G_4G_1}{C_2G_2G_3} \quad \text{...(15)}
\]
Fig. 7—Frequency response plots of CFA universal filter

Fig. 8—Notch filter response of CFA universal filter
For $C_1= C_2$ and $G_1= G_2 = G_1$ and $G_3 = G_2 = G$, Eqs (14) and (15) become

$$\omega_p = \frac{1}{CR_1} \quad \ldots (16a)$$

$$Q_p = \frac{R}{R_1} \quad \ldots (16b)$$

Equations (16a) and (16b) show an attractive feature of this circuit which is its linear relationship of quality factor with resistor $R$ and orthogonal adjustment of $Q_p$ and $\omega_p$. By simultaneously varying $R_1$ and $R_4$, $\omega_p$ can be tuned. Whereas by simultaneously varying $R_2$ and $R_3$ quality factor can be changed without disturbing the setting of $w_p$.

5 Simulation Results of CFA Universal Filter

The CFA-based universal filter obtained from OTA-CFA transformation using transformation method is designed for $f_p = 15.92$ kHz and $Q_p = 1$ is simulated using AD844A on the PSpice based software TINA Pro. The element values were $C_1 = C_2 = 10$ nF, and $R_1 = R_2 = R_3 = R_4 = 1$ kΩ. The simulation results are shown in Figs 7 and 8.

6 Sensitivity Figures

The active and passive sensitivity figures calculated for pole-$Q$-$Q_p$ and pole-frequency $\omega_p$ are given in Eq. (17)

$$S_{\alpha_1,\alpha_2,\beta_1,\beta_2,\beta_3}^{Q_1} = \frac{1}{2} \quad S_{\beta_1,\beta_2,\beta_3}^{Q_p} = \frac{1}{2} \quad \ldots (17)$$

where $\alpha_i$ and $\beta_i$ are current and voltage tracking errors of CFA’s for $i = 1, 2,$ and $3$ defined as $I_i = \alpha_i I$ and $V_o = \beta V$, where $\alpha = 1 - \varepsilon_1 \,(\varepsilon_1 << 1)$ and $\beta = 1 - \varepsilon_2 , \,(\varepsilon_2 << 1)$. It is observed that the active and passive sensitivity values are fairly low.

7 Conclusion

A new OTA-based voltage-mode filter is realized. The proposed circuit uses only two grounded capacitors and a minimum of four single output OTAs and realizes lowpass, bandpass and highpass filter functions. The notch filter can also be realized using an OTA summer. The $w_p$ and $Q_p$ can be independently tuned. In addition to the OTA universal filter, a CFA universal filter is also obtained simply by converting the proposed OTA circuit into CFA-based universal filter using transformation method. The CFA circuit is also simulated. The results of both the circuits are found to be verifying the theoretical claims. The working of both the universal filters is excellent. The sensitivity figures are fairly low.

References