DVCC Based K.H.N. Biquadratic Analog Filter with Digitally Controlled Variations

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Abstract In this paper, a digitally controlled single input multi output current-mode K.H.N. Biquad Filter is presented. The filter circuit is composed of three DVCCs together with four grounded resistors and two grounded capacitors. The digital control is incorporated using a current-summing network (CSN). Tuning of resonant frequency is carried out by 3-bit digital control word. Block by block replacement has been done to observe the change in the relationship between resonant frequency of the band-pass filter with the control word. The filter circuit showed three different variations when the DVCC blocks were replaced (one by one) with 3-bit DC-DVCC blocks. PSPICE simulations using TSMC 0.25 micron CMOS technology have been performed to validate the theoretical results.

Keywords: Current-mode, Differential Voltage Current Conveyor (DVCC), multifunctional filter, digitally controlled DVCC (DC-DVCC), Cut off frequency, K.H.N. Biquad filter

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1. Introduction

In the recent times the current mode filters have gained utility in various signal processing applications. These filters have revolutionized the modern day signal processing and have replaced their voltage mode counterparts in several of applications.

Moreover filters which could provide simultaneous realization of the basic filter functions have proved themselves useful in various applications which include touch-tone telephone tone decoder, phase-locked loop FM stereo demodulator and crossover network used in a three-way high-fidelity loudspeaker.

With the inception of Current Conveyors (CC), the filter design has reached a new height and various variants of CC have also gained attraction [1-10]. Various digitally controlled filters have been proposed and realized in the recent times. In [11] H.P. Chen and S.S. Shen presented a DVCC based Universal capacitor grounded voltage mode filter which realized all the five generic filter responses simultaneously. In [12] H. P. Chen presented tunable current mode universal filter, the high output impedance of this filter enable easy cascading in current-mode operation also in different modes of operation it could realize different filter responses simultaneously. Two years back I. A. Khan and A. M. Nahhas presented a CCII based reconfigurable first order multifunction filter whose frequency could be changed with a digital control word [13].

In this paper, the circuit proposed in [14] by Muhammed A. Ibrahim, Shahram Minaei and Hakan Kuntman, has been used to design and implement a digitally controlled current-mode K.H.N. biquad. Using grounded capacitors, the circuit becomes suitable for integration as the grounded capacitor circuit can compensate for the stray capacitances at the respective nodes. PSPICE simulations of the CMOS based programmable filter are performed to demonstrate results.

2. DVCC

DVCC is a five-terminal active analog building block illustrated in Figure 1, with terminal characteristics described by the following matrix equation [15].

\[
\begin{bmatrix}
I_{Y1} \\
I_{Y2} \\
V_X \\
I_{Z+} \\
I_{Z-}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
1 & -1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & -1 & 0
\end{bmatrix}
\begin{bmatrix}
V_{Y1} \\
V_{Y2} \\
I_X \\
V_{Z+} \\
V_{Z-}
\end{bmatrix}
\]

Figure 1. Symbol representing the dual output DVCC [15]
DVCC exhibits negligible (ideally zero) input resistance at terminal X, and very high (ideally infinite) resistance at both Y terminals as well as the Z terminal. The output current follows the input current direction with both currents flowing either into or out of the device. The CMOS implementation of DVCC is as shown in Figure 2.

IMPLEMENTATION OF KHN BIQUAD

The implemented KHN biquad is illustrated in Figure 3. The analysis of the circuit yields the following equations (2), (3) and (4).

\begin{align*}
I_{BP} &= \frac{s^2 R_1}{s^2 + \left( \frac{1}{R_2 C_1} \right) + \frac{1}{R_2 R_3 R_4 C_1 C_2}} \\
I_{HP} &= \frac{s^2 R_1}{s^2 + \left( \frac{1}{R_2 C_1} \right) + \frac{1}{R_2 R_3 R_4 C_1 C_2}} \\
I_{LP} &= \frac{R_1}{s^2 + \left( \frac{1}{R_2 C_1} \right) + \frac{1}{R_2 R_3 R_4 C_1 C_2}} \\
I_{IN} &= \frac{R_1}{s^2 + \left( \frac{1}{R_2 C_1} \right) + \frac{1}{R_2 R_3 R_4 C_1 C_2}}
\end{align*}

The resonant angular frequency \( \omega_0 \), and the quality factor, \( Q \), are given by (5) and (6) respectively.

\begin{align*}
\omega_0 &= \sqrt{\frac{R_1 C_1}{R_2 R_3 R_4 C_1 C_2}} \\
Q &= \sqrt{\frac{R_c C_1 C_2}{R_2 R_3 R_4 C_1 C_2}}
\end{align*}

We can see that lowpass, bandpass and highpass functions can be simultaneously realized without changing the topology.

In simulations, using PSPICE the DVCC was realized by the CMOS implementation shown in Figure 2 using TSMC 0.25-\( \mu \)m process parameters. The aspect ratios of the CMOS transistors of the DVCC are presented in Table I. The supply voltages were taken as, \( V_{DD} = V_{SS} = 2 \) V and the biasing voltages were assigned values, \( V_{B1} = -1.32 \) V and \( V_{B2} = +0.7 \) V. The circuit was designed for \( f = \frac{\omega_0}{2\pi} = 100 \) kHz and \( Q = 0.707 \) by choosing \( R_1 = R_2 = R_3 = R_4 = 1 \) k\( \Omega \) and \( C_2 = 2 C_1 = 1.125 \) nF. The responses of the multifunctional filter are shown in Figure 4 (a) and Figure 4 (b). The results are in full conformity with the theoretical analysis.

### Table I. Aspect ratios of the CMOS transistors of the DVCC

| Transistors | Width (\( \mu \)m) | Length (\( \mu \)m) |
|------------|-------------------|-------------------|
| M1-M4      | 1                 | 0.8               |
| M5-M6      | 24.2              | 0.8               |
| M7-M8      | 6.8               | 0.8               |
| M9-M13, M14 | 18.6              | 0.6               |
| M15-M19    | 25                | 0.8               |
| M16        | 19.6              | 0.8               |
| M18        | 18                | 0.8               |
| M19        | 20                | 0.6               |

3. DC-DVCC

To introduce the programmability in the multifunctional filter we have used a digitally controlled DVCC (DC-
DVCC) shown in Figure 5. The modified terminal characteristics for the same are as follows

\[
\begin{align*}
I_Y & = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\
I_Y & = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\
V_X & = 1 & -1 & 0 & 0 & 0 \\
I_{Z+} & = 0 & 0 & 0 & 0 \\
I_{Z-} & = 0 & -k & 0 & 0 \\
V_{Y1} \\
V_{Y2} \\
V_{Z+} \\
V_{Z-}
\end{pmatrix}
\end{align*}
\]

(7)

Where:

\[
k = \frac{I_{Z}}{I_X}
\]

(8)

For obtaining the digital control in the DVCC current summing networks (CSNs) are employed at the Z (Z+ and Z-) terminals for controlling the current transfer gain parameter k. The gain parameter k shows a variation from 1 to \((2^n - 1)\), where n is the number of transistor arrays. The modified circuit of DVCC with the transistors arrays is as shown in Figure 5. The CSN consists of n transistor pairs, the aspect ratios of whose PMOS and NMOS transistors respectively are given by:

\[
\begin{align*}
\frac{W_i}{L_i} &= 2^i \left( \frac{W_1}{L_1} \right) \\
\frac{W_i}{L_i} &= 2^i \left( \frac{W_1}{L_1} \right)
\end{align*}
\]

(9)

(10)

Furthermore, the current at the Z terminal which is assumed to be flowing out of the DC-DVCC, can be expressed by:

\[
I_z = \sum_{i=0}^{n-1} d_i 2^i (I_9 - I_{12})
\]

(11)

Therefore, the proposed DC-DVCC provides a current transfer gain, k equal to:

\[
k = \frac{I_{Z}}{I_X} = \frac{\sum_{i=0}^{n-1} d_i 2^i (I_9 - I_{12})}{(I_9 - I_{12})} = \sum_{i=0}^{n-1} d_i 2^i
\]

(12)

Where \(d_i\) are the bits applied to the i-th branch in the CSN. Now the current flow in a particular branch is enabled or disabled depending upon whether \(d_i\) is a logic 1 or logic 0 [16].

4. Comparative Study of Variation in Bandpass Filter Resonant Frequency

In this section the discussion is restricted to the variation in resonant frequency of Band Pass filter only. The circuit shown in Figure 3 was modified by replacing a DVCC block with a DC-DVCC block, one by one so that change in relationship between the resonant frequency and control word can be observed. Each block is assigned an individual gain \(\alpha, \beta, \) and \(\gamma\) respectively. The analysis is done and the following expression was obtained for the band pass response.

\[
\frac{I_{BP}}{I_{IN}} = -\frac{s \alpha \beta R_1}{s^2 + \alpha \left( \frac{1}{R_2 C_1} \right) + \frac{s \alpha \beta R_1}{R_2 R_3 R_4 C_1 C_2}}
\]

(13)

The resonant frequency is now defined as

\[
f = \frac{\sqrt{\frac{\alpha \beta R_1}{R_2 R_3 R_4 C_1 C_2}}}{R_2 R_3 R_4 C_1 C_2}
\]

(14)

As could be clearly seen from (14) the resonant frequency of the Bandpass filter can be controlled by changing the values of the gain parameters \(\alpha, \beta, \) and \(\gamma\). This variation will not require any change in the values of the passive components.

In the analysis that follows it is assumed that if the DVCC is replaced by DC-DVCC the gain parameter for respective block takes the value k, however if the DVCC is retained, the gain parameter attains value equal to 1.

Replacing the first block (corresponding to \(\alpha\)) by DC-DVCC, therefore for this configuration we have \(\alpha= k\) and \(\beta=\gamma= 1\), hence the equation for the band-pass response and the expression for the resonant frequency are respectively given by:

\[
\frac{I_{BP}}{I_{IN}} = -\frac{s^2 + \frac{k R_1}{R_2 R_3 C_1}}{s^2 + \frac{k R_1}{R_2 R_3 R_4 C_1 C_2}}
\]

(15)

(16)

The configuration is illustrated in Figure 6.
Figure 7(a). Simulated magnitude response (in dB) for band pass filter with control word \([d_2 \ d_1 \ d_0 = 0 \ 0 \ 1]\) selected for circuit of Figure 6.

Figure 7(b). Simulated magnitude response (in dB) for band pass filter with control word \([d_2 \ d_1 \ d_0 = 1 \ 1 \ 1]\) selected for circuit of Figure 6.

The simulations show a gradual increase in the resonant frequency when the control word is increased, the observations are recorded in Table II.

Now when the second block is replaced the value of the gain parameters changes to \(\alpha = \beta = \gamma = k\) hence the equation for the band-pass response and the expression for the resonant frequency are respectively given by:

\[
\frac{I_{BP}}{I_{IN}} = \frac{s}{s^2 + sk \left( \frac{1}{R_2C_1} \right) + \frac{k^2R_1}{R_2R_3C_1C_2}} \quad (17)
\]

\[
= k \sqrt{\frac{R_1}{R_2R_3R_4C_1C_2}} \quad (18)
\]

The configuration is illustrated in Figure 8.

Figure 8. Configuration for \(\alpha = k\) and \(\beta = \gamma = k\).

From (18) it is evident that the resonant frequency varies with the control word \(k\), in a linear fashion. The configuration shown in Figure 8 is simulated using PSPICE and the Bandpass responses obtained for the control word \([0 \ 0 \ 1]\) and \([1 \ 1 \ 1]\) are shown in Figure 9 (a) and Figure 9 (b).

Figure 9(a). Simulated magnitude response (in dB) for band pass filter with control word \([d_2 \ d_1 \ d_0 = 0 \ 0 \ 1]\) selected for circuit of Figure 8.

Figure 9(b). Simulated magnitude response (in dB) for band pass filter with control word \([d_2 \ d_1 \ d_0 = 1 \ 1 \ 1]\) selected for circuit of Figure 6.

The simulations show an increase in the resonant frequency when the control word is increased, the observations are recorded in Table 2.

When the third block is replaced the value of the gain parameters changes to \(\alpha = \beta = \gamma = k\) hence the equation for the band-pass response and the expression for the resonant frequency are respectively given by:

\[
\frac{I_{BP}}{I_{IN}} = \frac{s}{s^2 + sk \left( \frac{1}{R_2C_1} \right) + \frac{k^3R_1}{R_2R_3R_4C_1C_2}} \quad (19)
\]

\[
= k^{3/2} \sqrt{\frac{R_1}{R_2R_3R_4C_1C_2}} \quad (20)
\]

The configuration is illustrated in Figure 10.

Figure 10. Configuration for \(\alpha = \beta = \gamma = k\).

From (20) it is evident that the resonant frequency varies with the control word \(k\), in a \(k^{3/2}\) fashion. The
configuration shown in Figure 10 is simulated using PSPICE and the Bandpass responses obtained for the control word \([0 \ 0 \ 1]\) and \([1 \ 1 \ 1]\) are shown in Figure 11 (a) and Figure 11 (b).

The simulations show an increase in the resonant frequency when the control word is increased, the observations are recorded in Table 2.

The circuit presented in [14] for a particular design worked only for a single frequency but using the modification suggested in this paper the utility of the circuit is increased.

Now the circuit when selected for a particular variation and designed for a particular set of values of resistances and capacitances can work for seven different frequencies.

### Table 2. Variation in resonant frequency of bandpass responses with the control word

| Control word, k | Resonant frequency of BPF of Circuit of Figure 10 (kHz) \(\omega \propto k^{3/2}\) | Resonant frequency of BPF of Circuit of Figure 8 (kHz) \(\omega \propto k\) | Resonant frequency of BPF of Circuit of Figure 6 (kHz) \(\omega \propto \sqrt{k}\) |
|-----------------|---------------------------------|---------------------------------|---------------------------------|
| 1               | 97.79                           | 93.51                           | 95.63                           |
| 2               | 270.40                          | 187.00                          | 135.23                          |
| 3               | 491.75                          | 282.78                          | 166.29                          |
| 4               | 759.70                          | 380.27                          | 191.23                          |
| 5               | 1045.13                         | 475.54                          | 213.84                          |
| 6               | 1376.03                         | 568.66                          | 235.16                          |
| 7               | 1689.10                         | 661.28                          | 257.16                          |

Figure 12, Figure 13 and Figure 14 are the plots showing variation in resonant frequency of the Bandpass filter configurations shown in Figure 6, Figure 8, Figure 10.

Figure 12. Variation in resonant frequency of BPF with digital control word for circuit of Figure 6

Figure 13. Variation in resonant frequency of BPF with digital control word for circuit of Figure 8

Figure 14. Variation in resonant frequency of BPF with digital control word for circuit of Figure 10

The plots for the variation in resonant frequency obtained by simulation support the theoretical analysis. For the circuit in Figure 6 we have obtained a square root variation then linear variation is observed for the circuit of Figure 8 finally a variation directly proportional to \(k^{3/2}\) is observed for circuit of Figure 10.
5. Conclusion

In this paper, a digitally programmable current mode K.H.N. biquad filter based on three DVCCs was presented. Digital control has been achieved with the introduction of CSNs and variation of 3-bit digital control word (k). Now this circuit can be tuned for seven different frequencies for a particular design and variation. This multi frequency tenability within the same design is the contribution for this circuit. The circuit was configured in three different ways to provide different relation between resonant frequency of the Bandpass filter and the digital control word (k). The variations obtained were dependent upon the number of DC-DVCCs used. When a single DVCC was replaced with a DC-DVCC square root relation of Bandpass filter is directly proportional to $ka^2$, where 'a' is the number of DVCC replaced with DC-DVCC. The observations support the fact that the resonant frequency of Bandpass filter is directly proportional to $k^{3/2}$. Hence we obtained a circuit whose variation (relationship) of resonant frequency can be controlled. PSPICE simulations were carried out to verify the working of the digitally controlled K.H.N. Biquad Filter.

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